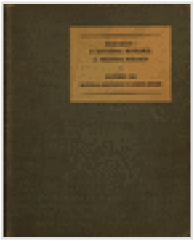

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RESEARCH—
A NATIONAL RESOURCE

II.—INDUSTRIAL RESEARCH

●

DECEMBER 1940

REPORT OF THE
NATIONAL RESEARCH COUNCIL
TO THE
NATIONAL RESOURCES PLANNING BOARD

UNITED STATES GOVERNMENT PRINTING OFFICE - - - - - - - - - - - - WASHINGTON : 1941

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EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL RESOURCES PLANNING BOARD

WASHINGTON, D. C., *April 4, 1941*.

The PRESIDENT,
The White House.

MY DEAR MR. PRESIDENT: We have the honor to submit herewith a report on "Research—A National Resource: Part II—Industrial Research".

This volume is the second in the series on this subject prepared under the general direction of our Science Committee with the cooperation of the councils which have designated members of the committee. The first part, submitted in 1938, dealt with "Relation of the Federal Government to Research", and a third part now in preparation is concerned with "Business Research". The document now submitted was prepared by a special committee of the National Research Council.

We endorse in principle the findings and recommendations of the special committee and wish to call attention to the great importance of industrial research in relation to both the present defense effort and also to developments in the post-defense period.

Sincerely yours,

FREDERIC A. DELANO, *Chairman*.
CHARLES E. MERRIAM.
GEORGE F. YANTIS.

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EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL RESOURCES PLANNING BOARD

WASHINGTON, D. C., *December 1, 1940.*

MR. FREDERIC A. DELANO,
Chairman, National Resources Planning Board,
Washington, D. C.

DEAR MR. DELANO: We have the honor to transmit herewith a report on "Industrial Research," constituting the second of a series of reports on the research resources of the United States. This report was prepared for the National Resources Planning Board by the National Research Council of the National Academy of Sciences. The National Research Council assigned the supervision of the preparation of this report to a Committee of 26 outstanding leaders in research. This Committee, known as the Committee of the National Research Council on Survey of Research in Industry, employed a staff of which Raymond Stevens, Vice President of Arthur D. Little, Inc., Cambridge, Mass., was the Director.

The report calls attention to the fact that the United States has achieved conspicuous leadership in industrial research. Since the beginning of this century, there has been a rapid development of research of the type with which the report deals. The intimate relations between industrial research and research carried on by the Federal Government and by other agencies, such as universities, is made clear in the report. It is also shown that industrial research has contributed very largely to the improvement of the standards of living.

The report contains a number of recommendations which the Science Committee commends to the favorable consideration of the National Resources Planning Board. The Science Committee calls special attention to the fact that this report was prepared by one of the councils represented in the membership of the Science Committee. It is the belief of the Science Committee that the Federal Government profits greatly by securing, as it has in this case, the services of a competent nongovernmental association of scholars.

Respectfully submitted.

EDWIN B. WILSON,
Chairman, Science Committee.

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DAVID L. EDSALL.
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ROSS G. HARRISON.
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CHARLES R. MOREY.
WILLIAM F. OGBURN.

NATIONAL RESEARCH COUNCIL
2101 CONSTITUTION AVENUE
WASHINGTON, D. C.

NOVEMBER 29, 1940.

MR. FREDERIC A. DELANO,
Chairman, National Resources Planning Board,
Washington, D. C.

MY DEAR MR. DELANO: In compliance with your request of December 8, 1938, addressed to the National Research Council, asking that the Council undertake a study of the research resources of industrial laboratories, I have the honor to transmit to you herewith a report entitled "Research—A National Resource. II. Industrial Research."

The report has been prepared under the supervision of a committee of the National Research Council, of 26 members, of which Mr. F. W. Willard is chairman, and with the assistance of a special staff under the direction of Mr. Raymond Stevens. Material for the report has been submitted by research workers in Government, industry, university, and professional fields. Unhesitant and unstinted cooperation has been obtained on all sides in the Council's endeavor to meet comprehensively and constructively the purpose of your request.

Respectfully submitted.

ROSS G. HARRISON, *Chairman.*

NATIONAL RESEARCH COUNCIL
2101 CONSTITUTION AVENUE
WASHINGTON, D. C.

SURVEY OF RESEARCH IN INDUSTRY

NOVEMBER 22, 1940.

DR. FRANK B. JEWETT,
President, National Academy of Sciences,
Washington, D. C.

DR. ROSS G. HARRISON,
Chairman, National Research Council,
Washington, D. C.

GENTLEMEN: I have the honor to transmit the attached report of the National Research Council's Committee on the Survey of Research in Industry.

It is my duty to record here the gratitude of your Committee to the leaders of private enterprise in the United States of America who have, without exception and without reservations, responded to your Committee's requests for information. Lacking this wholehearted cooperation, your Committee's task could not have been performed.

To those men eminent in their respective fields who have prepared monographs for this report, your Committee records its grateful appreciation.

To Mr. Raymond Stevens, Director of the Survey, and his staff, your Committee acknowledges its debt. They have performed a difficult task expeditiously, economically, and with an intelligent discrimination of relative values.

Respectfully submitted.

F. W. WILLARD, *Chairman.*

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INDUSTRIAL RESEARCH

Contents

ILLUSTRATIONS

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Findings

1. Continuous and increasing application of science by industry is contributing most significantly to the high standard of American living. Viewed in this light industrial research is a major national resource.

2. The United States has become the acknowledged leader in industrial research.

3. American industry employs over 70,000 research workers in over 2,200 laboratories at an estimated annual cost, based on an average of figures reported, of the order of $300,000,000.

4. Industrial research is generally accepted both by informed labor and by informed management as a desirable and constructive force. Organized labor is officially on record in favor of research, and the annual reports of many of the most successful corporations have stressed the relation of research to earning power.

5. Small and moderate-sized companies were found whose principal means of competitive defense against larger companies is industrial research. One company mentioned specifically that, as a defense against competition from a merger of other companies in the industry, a policy of research was adopted and special products were developed, and in consequence there has been continuing heavy demand.

6. One-hundred eighty-one manufacturers report expenditures for industrial research of 2 percent of gross income as a median, the percent varying with company size and from one industry to another.

7. Industrial research is possible for all industrial units, small and large. The distribution of research in industry seems to follow no definite rule but to depend rather upon management policy. It is apparent that research is most active in companies utilizing technically trained men in design, production, or sales activity.

8. Industrial research acts as a protection against unfavorable changes taking place both within and without an industry.

9. A great difference exists in the direct utilization of research by different industries—a few industries still depend almost altogether upon sources of supply for their technical advance while others have themselves made great strides in the application of science.

10. Industry looks to the universities for trained technical men, and for principal advances on the frontiers of science. However, it is of interest that advances are not infrequently made on these frontiers in the course of research projects originally designed to achieve immediate commercial objectives.

11. The United States is now virtually independent of foreign sources for adequate apparatus and facilities for laboratory research.

12. Cooperation and coordination in industrial research take various forms. Some industries cooperate through associations, especially in studying problems common to an industry. Frequent instances of cooperation between noncompeting companies are noted. It is the belief of those responsible for this report that the danger of unnecessary duplication of research by competitive industry will remain slight. No special steps are recommended at this time to improve coordination and to prevent duplication.

12. Relations between research men in Government and in industry are, in general, close and cordial. Industry generally is continuously cooperating reciprocally with the Army and Navy and with the technical branches of other departments and bureaus in the Government. A factor reported as interfering to some degree with even more effective use of industrial cooperation by War and Navy Departments is the extension of secrecy to the point of not informing industry freely of troublesome problems. It is possible that less restriction might be placed on information about existence and nature of problems, while at the same time taking care that the solutions, when found, are treated with discretion.

13. Some branches of applied science are more highly developed in industry than others. Notably chemistry has been widely accepted and applied, and well over a quarter of the members of industrial research staffs are chemists or chemical engineers. Biology, however, has not obtained the same general acceptance even in the food industries where there is great opportunity for wider utilization of applied biology. It is believed that the biologists themselves could take steps toward correcting this situation, as did the physicists in the formation and operation of the American Institute of Physics.

14. There is opportunity for some American university to establish a comprehensive curriculum in applied mathematics. The number of men engaged in applied mathematics is comparatively small but their work is extremely significant. It could be made even more significant through special educational facilities.

15. Industrial research men are members of a profession with high ethical standards. Compensation for industrial scientists is in general comparable with that for men with equivalent responsibility elsewhere in industry.

16. Industrial research has an ever-widening field, and shows no tendency to terminate or even to be restricted for lack of new opportunity.

Recommendations

TO INDUSTRY:

1. Several large industries are found to lack extensive provision for research. It is recommended that leaders in such industries associate themselves with representatives of the National Research Council in a systematically organized investigation of the possibilities of their undertaking industrial research, and of practical ways and means for realizing the possibilities.

2. Although no attempt is made in this report to define a procedure for initiating research, the various studies and the introduction suggest several sources of information and cooperation in providing for research. It is recommended to companies not now conducting research, that they consult one or several of the sources of cooperation indicated in this report and consider carefully the establishment of research as a continuing activity. The section on small industries and the introduction, in particular, may be found helpful for this purpose.

3. In order that more extensive and effective application of the biological sciences in the food industry may be encouraged, it is recommended to companies in the prepared and preserved food fields, that common ground be sought for the joint support of fundamental biological research.

4. Some companies publish scientific findings regularly, and, in general, publication is permitted when protection of the new findings has been assured. In the opinion and experience of the committee, industries have not only not suffered, but have profited by adopting a liberal publication policy.

TO LABOR AND INDUSTRY:

5. An almost untouched and extremely profitable field for cooperation is believed to exist in the conduct of research on fatigue and related matters affecting the welfare of labor, and thus, also, industry. It is recommended that labor and industry join in initiating systematic research in this field.

TO GOVERNMENT:

6. Industrial research as a national resource capable of contributing to public welfare should be fostered. Any restrictive policies on research on the part of Government are opposed to the public interest. For example, any tendency toward insisting upon capitalization of research expenditures for tax purposes might prove a dangerous threat to the welfare of industrial research.

7. In several branches of pure and applied science, abstracts of the technical literature are supported by scientific societies. Such support is becoming increasingly burdensome and increasingly inadequate in the face of the enormous and rapidly expanding amount of technical matter being published. An excellent means of Government contribution to industry would be proper provision for systematic and complete publication of abstracts of scientific and technical literature.

8. Provision should be made for the extension and revision of the International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, originally published in 1926 under the auspices of the International Research Council and the National Academy of Sciences. These critical tables are the principal combined source of authentic records of properties of materials. As such they should be brought and kept up-to-date.

9. Extension of research means increasing dependence upon adequate and correct standards of reference. Establishment of standards requires most exacting and long-continued laboratory work, a high caliber of technical personnel, and, frequently, expensive facilities. There is need for much more research on standards of measurement than is now conducted, and it is recommended that the National Bureau of Standards be given encouragement and increased tangible support for research on standards. It is also recommended that any appropriations for such support provide ample funds for adequate publication and distribution of the Bureau's findings.

10. In order that findings of Government laboratories generally be made readily and continuously available to industry, it is recommended that Government bureaus receiving appropriations for scientific work be less restricted than at present in allowances for representation at technical meetings, for publication of findings, and in general, for cooperation with industrial technical workers.

SECTION I

A REPORT ON INDUSTRIAL RESEARCH AS A NATIONAL RESOURCE—INTRODUCTION

Contents

SECTION I

A REPORT ON INDUSTRIAL RESEARCH AS A NATIONAL RESOURCE—INTRODUCTION

By Raymond Stevens

Vice President, Arthur D. Little, Inc., Cambridge, Mass., Director, Survey of Research in Industry

Purpose

This report on industrial research in the United States is presented by the National Research Council, at the request of the National Resources Planning Board, as one of a series on research as a national resource. In accordance with the general specifications suggested for it, the report discusses the nature, extent and welfare of industrial research but does not attempt a catalog of new wealth coming from the laboratories.

Even a cursory review of the work in the various applied sciences will show the wealth-producing nature of industrial research. It is a resource with promising new areas under development and with no sign of depletion. The first of the applied sciences to be exploited in the industrial laboratories still produces in amounts apparently inexhaustible.

Considered as an industry by itself, industrial research is not small, as it employs over 70,000 people, but it is based on the work of a comparatively small group of specially qualified men. The activities, objectives and policies of research men are described in this report in studies in which they themselves discuss the state of their several applied sciences. In some instances means are suggested by which their branches of research may be fostered.

Scope

An endeavor has been made to canvass the known industrial laboratories in the country, bringing up to date previous statistical information and supplementing it with new data. This material is summarized in the section on Location and Extent of Research Activity in the United States. A directory of all laboratories thus canvassed will be published separately by the Council. In most of the remainder of the report, however, emphasis has been placed on less tangible aspects.

The brief review of research policies abroad has been considered desirable for comparative purposes, while the review of the origin and growth of industrial research in the United States is intended as an aid in the proper comprehension of the research structure as it now exists. The present status of industrial research in three different industries is described to illustrate the work of physicists, chemists, and aeronautical engineers in aeronautics; chemists and chemical engineers in the petroleum industry; and metallurgists with iron and steel.

A few special aspects of research are discussed in some detail, but notable omissions are due to the belief that the matter is covered in publications readily available and listed in the bibliography.

In particular, organizational relationship of research, the subject of several surveys and reports, is not covered by a separate study, although it is touched upon briefly in this introduction. One obvious omission, any discussion of patent policy, is significant, as patent policy has important bearing on the health and growth of industrial research. What that bearing is, and what, if anything, should be done about the present patent system, is the subject of other current investigations, more detailed and extensive than could be included here.[1] It is generally recognized, however, that patents play an important part in the motivation of research, and no changes in the patent system should be made without most careful consideration of possible effects on the welfare of industrial research.

Another omission will bear comment: The tie between industrial research organization and the university is close and friendly, with recognition of mutual dependence. Work on the frontiers of science is carried on principally in the university, from which the stream of youth carries its results continuously into industry. No study of industrial research can be complete without consideration of research work and policies in the universities. Some aspects of university research were covered in the preceding report (that on Government research) but a more extensive review is desirable.

The authors of the various studies have been the final authority on content and wording of their sections and to them must go both credit and responsibility for the facts, conclusions, and recommendations they present.

The Nature of Industrial Research

The Century Dictionary defines research as "A continued careful inquiry or investigation into a subject

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[1] The Conference Board and American Engineering Council. Joint patent inquiry for the National Association of Manufacturers, 1940.

in order to discover facts or principles," and there are other good definitions, such as this: "Research is the organized and systematic search for new knowledge." Unless these broad definitions are limited, however, research may include many and, at times, curious activities. "Research" may determine the type of radio program preferred by the largest number of customers in a particular income class, or the market available for automatic pencils. "Research" may ascertain the cost of manufacture of dry batteries, or the preferred practice in operating purchasing departments. "Research" may disclose the designs used by various nationalities for foot coverings, and lead to new styles in shoes. All these activities can be called "research," and all may be conducted by industry—yet none is what is here termed "industrial research."

Industrial research as the activity of over 2,200 industrial laboratories consists of organized and systematic search for new scientific facts and principles which may be applicable to the creation of new wealth, and presupposes the employment of men educated in the various scientific disciplines. The line of demarcation between such research and the technical utilization of research findings is seldom clearly defined. Usually the initial stages of commercialization are carried on under laboratory auspices. There is wide difference of opinion as to the point at which "research" stops and commercial development and operation begin.

Attempts have been made to classify the stages through which research travels on its way toward adoption of results by industry. At the foundation of all industrial research is a type referred to, in this report, as "fundamental" and because such research offers best promise of new industries and of major contributions to old industries, special consideration is given it in this report. Dr. C. M. A. Stine in his section describes "fundamental research" as "quest for facts about the properties and behaviour of matter, without regard to a specific application of the facts discovered." One stage removed is "pioneering research," and the distinction made is principally one of objective. If a definite objective is stated, particularly if it applies to specific manufactured products, "the work becomes pioneering applied research." "The investigation of monomolecular films by a producer of electrical equipment might be fundamental research, whereas the investigation of monomolecular films by an oil refiner engaged in the production of lubricants might largely assume the complexion of applied research. The complexion of the research depends upon the character of the problem and the nature of the agency carrying on the investigation."

Once an opportunity for commercial development becomes apparent, there is usually a period in which "test-tube" or "bench" research is conducted. Apparatus used is extremely limited and usually relatively crude. This has been true, for example, in the development of most of the plastics that have attained such wide acceptance. It avoids heavy expenditures in equipment or personnel in a project which at this stage is in effect a speculation.

Following the bench stage there comes the pilot plant. For example, in the manufacture of spun glass a small unit was developed and operated for a considerable period. It was not expected that the product

FIGURE 1.—Research Laboratories, General Electric Company, Schenectady, New York

of this unit would be acceptable commercially, and many changes were anticipated before the desired product and procedure were achieved. These variations in the process could be made without enormous expense, and mistakes on this scale are not ruinous. As the process was then still in the research stage, various trials could be conducted without delaying production or interfering with the momentum of commercial operation. In this instance, for example, the high-speed-photography method was applied to the study of glass spinning and this made various refinements possible.

Research continues after the product is in actual production. Obtaining a satisfactory coating for glass fibers, as for air filters, for example, is typical of the product-improvement assignment frequently received by the research laboratory. At the same time investigations are made of various applications when the fringe between sales and research has been reached. Commonly, in the market introduction of a new article research men cooperate with the sales force and frequently even become salesmen themselves temporarily.

When market or production difficulties cannot readily be solved by production or sales personnel, members of the research staff are frequently called upon to assist. Experience with the initial coating of photographic plates is typical of the kind of trouble that develops after the product is already on the market. The coating of these plates proved to have poor keeping qualities for unknown reasons. By dint of careful investigation it was eventually found that the difficulty was in the gelatin and that a special type was necessary. Such investigations are frequently known by research men as "trouble shooting."

As a final stage in the development of a new process or product, technical control of process and quality is frequently established, providing for analyses or tests at various points in order to maintain the original procedure and the standards established.

In this gradation from fundamental or pioneering research down to "trouble shooting" various steps and "types" of research have been recognized by authors and research men. Routine testing and production control are generally considered outside the definition, but there is no such general agreement on other fringes of research, as for example, at the border line between research in applied physics and the design of new mechanisms. Some research laboratory organizations include design personnel that in others would be included in engineering departments.

It will also be apparent that dependence upon organization differentiates modern industrial research from the practice of the individual inventor. In a typical project a new type of yeast is noted by a research bacteriologist, possibly a variation giving better flavor or greater yield. It is investigated in the test-tube stage, and its preferred nutrients and

FIGURE 2.—Research Laboratories, American Cyanamid Company, Stamford, Connecticut

growing conditions are determined. Then a chemist investigates commercial nutrients, and possibly a compromise is reached with the bacteriologist between the ideal and the practical. Then a chemical engineer designs and operates a pilot plant, and later a full scale plant is designed, installed, and initially operated, possibly with the help of other engineers. The director of research is responsible for the coordination of the work of the biologist, the chemist, and the engineers as the project goes forward through successive stages. Modern research laboratories thus utilize men trained in the various sciences, drawing together a variety of disciplines.

Research has been called "an attitude of mind" and is, after all, the sum total of thought and activity of research men. The early protagonists of industrial research had in mind a practical constructive force that promised great things for humanity; in the pursuit of research they found adventure and the zeal and satisfaction of the crusader. No brief dictionary-type definition conveys any understanding of what these research men themselves meant when they used the term "research."

The best practical definition appears to be a description of industrial research in its various aspects, and such a description is presented here in the several studies written by research men. Differences of opinion on terminology will be noted, but the composite should give reasonably satisfactory comprehension of the term. In spite of the differences, one common denominator will be noted—the sincere endeavor of all true industrial research men to work toward making available to the public greater physical wealth and well-being.

Research Personnel

A few requisites for research men are generally recognized and first among them is intellectual integrity—the ability to recognize truth, and the willingness to accept it. Technical competence is assumed, but a number of personal qualifications are considered of such significance that they are discussed in some detail in the study of Careers in Research. The individual who qualifies fully for true research is rare, but "the field of industrial research is so broad that there is no standard type of individual for whom specifications can be drawn."

In most research organizations, a man with the proper qualifications can find a life career with tangible compensation generally on a par with or even above that of technically trained men with equivalent responsibilities elsewhere in the company.[2] Frequently men are transferred to operating or sales positions because of individual qualifications and preferences, and such transfers usually result in more effective liaison between research and operating departments.

As contrasted with many other fields, research is a profession in which, because it depends so largely on individual expression, workers cannot well be classified on a salary or any other basis. Men with high creative urge and scientific curiosity find satisfaction in initiating improvements that others may carry forward to the great benefit of employer and consumer. Association with others of similar interests and intellectual activity makes a strong appeal. Recognition through publication, permitted by most industrial research laboratories when it is not prejudicial to company interest, is a source of considerable satisfaction.

With the present enormous mass of technical data available, the research personnel serves as an intelligence department to the modern company. Properly organized and managed, such a department frequently makes unnecessary any formal exchange of information between companies—all draw from the same reservoir; and occasionally identical advances occur simultaneously in several companies, as was true with solvent refining in the petroleum industry. The uniform level of advancement within industries maintaining research—petroleum is only a conspicuous example—indicates a constant and rapid transfer and development of technical intelligence through normal channels, usually without the necessity for official agreements. In some smaller companies much of the time of research men is given to keeping in touch with technical advances in universities, in reading pertinent technical publications, and in conferring with technical sales-service men from the larger manufacturers. Companies lacking technically trained men for such "intelligence service" are at a disadvantage and even find difficulty in fully using the technical assistance offered by sales-service men or professional consultants.

Practice as to publication of research findings varies from company to company. At one extreme is the company unwilling to let the name or number of its research personnel be known; most companies are less secretive and permit occasional publication and encourage staff members to attend the scientific meetings. At the other extreme are companies which themselves publish scientific papers and consider such publication not only as a form of building "good will" and prestige, but as serving the public welfare and particularly as assisting in the further development of their research men. In many instances, at least, publication has resulted in professional advancement to the individual, and both through his development and through associations created with scientific workers in related fields, has benefited his employer.

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[2] White, Alfred H. Occupations and earnings of chemical engineering graduates. *American Institute of Chemical Engineers, Transactions, 27,* 235 (1931).

Place of Industrial Research in the Industrial Organization

It is generally accepted that research, as a staff function, receives the direct attention and policy supervision of the principal executive management of the industrial corporation. There is no standard pattern for the place of the research department in the organization, however, and occasional attempts are still made to subordinate research to production, sales, or other functions. Where research has been successfully established on a continuing basis, such subordination to other functions is not general practice.

Committee management is found to be more frequent for research than in other organizational units in industry. Such committees represent other major divisions and define broad research objectives, establish policies, and exercise financial control. The research director supervises the research within the limits thus imposed. In the absence of such practice, equivalent provision for cooperation with other departments usually is provided.

In a majority of companies questioned on the subject, the final decision in authorizing individual research and development projects rests with an officer of the company, most frequently the president; only 19 percent rely upon a committee, with the president usually a member.[3] This may be the executive or management committee, although special research committees, planning committees, "construction and experimental" committees, and budget committees are mentioned.

No standard practice has been found for the determination of the amount to be spent by a company on research. Some companies attempt to establish a relation between expected value and the budget, a basis requiring rather clearly defined objectives. A few set aside a percentage of gross sales, while most use a combination of methods.[4] The proper ratio cannot easily be determined, since it varies with the nature of the product, the value added by manufacture, size of company, and many other factors. Inquiry in a variety of industries has shown, however, that percentages amounting to from ½ to 3 percent of gross sales are frequently found where research is well established. As low as one-tenth of 1 percent or less may be found within the packing industry, for example, while in chemicals 5 or more percent of gross income is frequently noted.

Estimates or even records of amounts expended for research are difficult to secure because of the loose definition of the term. It is seldom possible to attain unanimity of opinion, even within one company, as to what constitutes research. In particular, quality control tests and analyses frequently contribute to product improvement and may in part properly be called research; similarly "trouble shooting," routine investigation of production or sales difficulties, may lead to change of process or product. Costs reported most carefully may not be presented on a basis directly comparable with figures from other companies prepared with equal care.

The principal expense in research laboratories is in wages and salaries, occasionally of the order of 75 or more percent.[5] For the purpose of estimating amounts spent by industry on research, a figure of $5,000 per man per year has been used frequently by well informed research executives. Recent sampling inquiry of a number of laboratories for the purpose of this report gives an average annual cost per man of approximately $4,000. This cost includes both professional and nonprofessional men as reported in the National Research Council Directory of Industrial Research Laboratories. Such an average per person cost cannot safely be used for any one company as wide variation—from $2,500 to over $9,000—is shown on the returns made. An average figure of between $4,000 and $5,000, however, is considered reliable in estimating the total amount spent by industry or any large section of industry on industrial research. In the present canvass of laboratories, over 70,000 research workers have been reported. Close estimates are out of the question because there is no precise and generally accepted definition, but on the basis of this number of men and the average cost per man indicated, it may be estimated in round figures that American industry is spending over $300,000,000 per year on research.

It is impossible to measure the indirect benefit of organized industrial research, but it is often claimed that research benefits management, since it increases flexibility in the face of changing conditions and leads to the adoption of research methods in management practice. Many annual corporation reports have cited organized research as contributing to growth and strength. A comparison of a group of companies known to maintain strong research departments with another group taken at random will show how research and successful management run together. Whether research is a significant factor in aiding good management or whether it has merely been adopted by such management is not easily demonstrated.

The relationship of labor to industrial research involves chiefly the somewhat controversial question of technological unemployment. As contrasted with labor-saving equipment, consolidations, plant relocations, and many phases of technological changes, industrial

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[3] *National Association of Cost Accountants Bulletin*, XX, No. 13, Sec. III (March 1939).

[4] Chamber of Commerce of the United States, Department of Manufacture. Budgetary and accounting procedures for organized industrial research. Washington, D. C., Chamber of Commerce of the United States, 1937, pp. 4, 5.

[5] Transcript of discussion. Meeting, Committee on Survey of Research in Industry, December 6, 1939, p. 12.

research serves rather to increase or stabilize employment. Organized labor has officially recorded its active approval of the encouragement of applied science, and informed thought in the fields of labor organization and of sociology recognize technological advancement as both desirable and inevitable.[6]

One important phase of labor relations concerns the temporary effect upon employment of any change whatever, including changes produced by organized industrial research. Within an industry the necessity of reducing the effect of change upon employment presents a problem to management. Procedures have been proposed, for example, in the railroad industry[7] recognizing and providing for employee displacement due to labor saving improvement. Labor approves technological advances in general while endeavoring to alleviate immediate and temporary unemployment consequences,[8] [9] and to increase participation in economic benefits.

FIGURE 3.—Bell Telephone Laboratories, New York, New York

Procedures within an industry do not solve the problem of obsolescence of a whole industry—the buggy and buggy-whip industries are classic examples. Unemployment insurance can reduce the shock, but it is far from the complete answer. Well-organized industrial research within the industry is in itself a protection against such obsolescence and the history of the fall of the phonograph before the advance of radio and its subsequent aggressive and successful revival as a result of research personnel and method is cited to illustrate profitable economic policy as well as sound sociological practice.

There may be significance in the relation to employment stability of the number of research workers employed by a given company. The 6 industrial groups reporting the largest percentage of research workers per 10,000 wage earners in 1937 were chemicals, radio apparatus and phonographs, petroleum, rubber, electrical machinery and apparatus and electrical communication.[10] These groups, as a whole, stand in favorable comparison to the balance of industry in the continuity of employment and in the relative absence of temporary displacement resulting from technological advancement or other causes. Although factors other than research were also at work, including general good management, there is little question that research organizations played an important part in stability of employment.

Research in the National Economy

The rapidity with which research has taken its present significant place in industry is indicated in the discussion of its origin and growth. There was a long slow period, prior to the turn of the century, a period largely used in accumulating the great reservoir of scientific knowledge to be drawn on later, though there were many important examples of the commercial application of science. But shortly after 1900 industry generally began to accept research, organized research departments began to appear, and the commercial and sociological significance of organized research began to be apparent.

In the discussion of growth and development it will be noted that companies whose operations were based on scientific discoveries were among the first to adopt organized research. Among them will now be found some of the country's largest and most important laboratories. In this record of growth will also be seen the close relation between the universities and the laboratories. It would appear that there was mutual

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[6] Reported at conference arranged by Beyer, Otto S., Chairman, National Mediation Board for Survey of Research in Industry.

[7] Report of the Federal coordinator of transportation, 1934. Washington, U. S. Government Printing Office, 1935, House Document No. 89.

[8] *Proceedings, 40th Annual Convention American Federation of Labor*, Resolution No. 65.

[9] Murray, Philip, Chairman steel workers organizing committee. Verbatim record of the proceedings of the Temporary National Economic Committee. *Proceedings of the Temporary National Economic Committee, 13.* No. 5, 145-96 (April 12, 1940).

[10] Perazich, G., and Field, P. M. Industrial research and changing technology. Philadelphia, Pa., Work Projects Administration, National Research Project, *Report No. M-4*, 1940.

dependence and that the very considerable increases in numbers of technical students and in courses in applied science were due to the demand being created by the laboratories. In turn, technical graduates initiated research in companies where it was previously unknown. Naturally, research prospered best in the newer companies, dependent upon technical men, and it has made least progress generally in the old, established industries where the art had been highly developed, as in the tanning industry, to cite an extreme example.

As a distinguishing characteristic of modern research is its organization, it is to be expected that it would be most highly developed in the larger companies. It is probable that in some instances an aggressive research policy has contributed to the rapid expansion of some of these larger companies. In the course of the survey, question was raised as to the ability of the small company to use research and as this problem had important bearing on public welfare, it was given special consideration.

Briefly, it would appear that although the small company has many handicaps, in the use of advertising, accounting, legal assistance, and other staff functions, when it comes to research it is often found that a small flexible group can accomplish rather remarkable results. One company reported that when a large portion of the industry merged and offered unusually strong competition, the company fell back upon research as a defense. As a result, specialties were developed that have kept the company in a strong position with increasing, rather than decreasing, pay roll. In many other instances, especially in industries built upon new discoveries, small companies lean upon research and technical development as a principal competitive support.

Research and the Small Company

There is a lower limit for the average size of company that maintains a large organized research staff. Assuming 3 percent of gross income as proper for research, then $30,000 is a reasonable budget figure for a company whose annual gross income is $1,000,000. This would mean a research staff of six or seven people at an annual carrying cost approaching $5,000 per person. Obviously large research staffs are not to be expected in the smaller companies.

It does not follow that small companies are not using industrial research. Unfortunately, the National Research Council's Directories of Industrial Research Laboratories are not a satisfactory source of small-company research statistics, since small companies were not canvassed systematically even for the latest directory. For this report a sampling investigation was necessary and its findings have been used. For conclusive statistical data on the extent of small-company research, for comparison with large companies, or with estimates of totals spent for other purposes, a much more extensive census would be necessary. Relatively little use was cited of university, consulting, association or governmental laboratories. Small companies appear rather as highly individualistic and self-sufficient.

A variety of successful research practices is found in small companies as are numerous methods of providing for advertising, legal, and accounting procedure, and other staff functions without separate departments or organized staffs. Increasingly common and constructive is the use of help from the technical sales-service man who relays to his customer technical and even original research assistance in the application of his materials. An electrical company carries on research in electronic circuits, doing pioneer work in the field, and its findings are available to customers, small and large. Paint, lacquer, and resin manufacturers have aided small companies in the improvement of their products by special finishes, frequently involving special original research. The small shoe manufacturer obtains his research from suppliers of machinery or materials, some of whom have large laboratories. The flow of technical knowledge from the research laboratory of the large company to the small company and through its sales engineers to the ultimate user or consumer takes the place of highly organized research in many small companies.

FIGURE 4.—General Motors Research Laboratories Building, Detroit, Michigan

Association research is used in some industries although less emphasized proportionately in the United States than in England. The American Institute of Laundering has an excellent laboratory serving the whole industry. Canners are served by a laboratory with an excellent record of achievement, and the association even maintains a traveling laboratory that follows the seasons from small cannery to small cannery. A central laboratory in the paint and varnish industry not only solved many minor problems but has introduced new oils to meet increased difficulty in obtaining supplies from the Orient. Such association laboratories are available to all members, and most of them issue reports at intervals, render advisory service, and even undertake individual investigation

Contrary to a common understanding, the larger laboratories available under fellowship or consulting arrangement are not used exclusively by companies without research facilities. Sponsors of research at foundations and at commercial consulting laboratories include many companies well known for their own facilities, personnel, and progress in research.

The large consulting laboratories are coordinating units in touch with many noncompetitive industries. Services of such organizations, however, are available to the small company at costs equivalent to those of the maintenance of one or two research men, and special arrangements are frequently made by companies with much more limited budgets.

The principal consulting laboratories are found prepared to suggest sources of research aid, and they indicate no lack of research assistance and cooperation available from various sources when sought. Banks can report on the financial standing of consultants, and many of them are now offering information on availability of research aid as a special service to customers. One group of bankers even serves as an intermediary between question and answer on specific technical problems. In the utilization of outside facilities for new product or process development or for other major projects, however, the small company is faced with the same necessity for patient diligence as are the larger laboratories, for major research projects generally require a period of years for their development.

Some small companies use individual consultants to advantage. The industrial areas of the country are dotted with consultants available to industry and the best among them provide the equivalent of the research available to the largest companies. The Engineering Societies of New England has compiled a directory of research consultants of various types in the section, and it lists 289 entries of individuals and institutions covering the whole field of science and engineering.[11]

Numerous small manufacturing companies have employed one or more technically trained men for production or other duties, who carry on research or draw intelligently upon the extensive available sources of technical aid. In some instances, such men have met outstanding success. An extension of the practice of employing technical graduates appears worthy of any possible encouragement.

"Examples of Research in Industry"

Research would appear to follow a general pattern in a particular industry with a notable similarity between laboratories and policies within the industry as contrasted with laboratories and policies in other industries. No adequate explanation of the reasons for particular policies in the different industries has been offered—whether they are dependent largely upon the technology in an industry or upon mere chance in development is not yet certain, nor will it probably be known until research has had opportunity for further development, particularly in some of the older industries. The three industries chosen for illustration make these conditions apparent. It is even true that the word "research" in some industries carries different connotation than in others.

At times in the past there has been a tendency to criticize whole industries for not adopting aggressive research policies. When such criticism is based upon comparison between industries, however, it is seldom valid. In the chemical industry research is not only necessary but at present can be compared almost directly with the design and engineering departments of the automobile industry. Some types of new chemicals can be created by the research department almost to order. The textile-finishing industry, however, is chemical and was built upon the research of Dana, Mercer, and other early chemists, but various attempts at the application of research to textile finishing have shown that the opportunity is by no means as obvious as in the chemical industry. Until some more promising approach to textile-finishing research becomes apparent it probably would be poor judgment for companies in that industry to spend the high percentages of gross income being devoted profitably to research by the chemical industry.

It is not always true, however, that failure to adopt research is due to lack of apparent opportunity. England, Soviet Russia, and Germany have done more on the utilization of coal than has the United States. This country has not yet the need that spurred Germany to the conversion of coal to petroleum substitutes; but this country has a coal problem, and industrial research, properly supported and conducted, might assist in the solution. Unfortunately, the coal industry is not prosperous and is not expanding. Within itself it does not

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[11] Directory of New England research and engineering facilities. Boston, Engineering Societies of New England, Inc., 1939.

contain the setting that has made research so constructive in the petroleum industry, for example. To a lesser degree, the railroad industry is in the same position. If this is a fault, it does not necessarily lie with the industries but rather with the fact that the problem of how to initiate and support research within an industry not generally making reasonable progress has not been solved adequately. The subject needs study.

Location and Extent of Research Activity in the United States

An extensive analysis of the incidence of industrial research, based upon directories published by the National Research Council has recently been made.[12] The present report therefore devotes relatively brief space to the subject. The few charts presented, however, are based upon additional recent data obtained by canvass made for this purpose. Only such charts are included as bear upon policy matters with which this survey and report are directly concerned. Supplementing a questionnaire canvass of all laboratories known to the Council and of members of the National Association of Manufacturers and other companies, members of the survey staff personally canvassed a representative sample of industry, seeking answers to specific questions. It is believed that the information presented as a result of this sampling can be accepted as objective and representative.

Organized research laboratories are found in all the industrial areas in the country and in most types of industry. It is apparent that research has become well established as a continuing function and that its further spread may be anticipated. Of particular interest is the chart[13] showing the rate at which the number of laboratories has been increasing—and it should be borne in mind constantly that the list of organized research laboratories recorded in the directory is by no means a complete record of the provision for research in American industry.

Research Abroad

Industrial research was well developed in Europe before its general adoption in America, but the United States now leads in total spent on research and except possibly for the Soviet Union in ratio of research expenditures to national income. Satisfactory figures are not available, but Bernal has estimated that we spend more on research than all the rest of the world, outside the Soviet Union, and that England and Germany spend possibly a tenth as much, France and Italy appreciably less.[14]

Excellent and extensive laboratories are found in Soviet Russia and Japan. Each of the smaller industrial countries provides for research. Switzerland, for example, makes up in quality for part of its lack in quantity. Research is generally recognized as a factor in international as well as in national industrial competition and development.

England's Department of Scientific and Industrial Research is an outstanding example of government encouragement and support of research for the benefit of industry. The World War had shown the competitive power of research—

> and there was general awakening to the fact that for success in times of peace as well as of war, it was desirable that the sources of science should be utilized to the full. The perils of war furnished precepts for peace, and it was realized that on the conclusion of the conflict a situation would arise in the world of industry which would call for increased effort if British industrial supremacy was to be maintained, and if the manufactured products of the nation were to continue to hold their own in the world's markets. In anticipation of that situation the Government of the day set up the Department of Scientific and Industrial Research and as part of the financial provision placed at its disposal, Parliament voted a capital sum of one million pounds for the encouragement of industrial research. The most effective way of promoting this aim was the subject of careful consideration by our predecessors in consultation with leaders of industry and the scheme of cooperative research was devised.[15]

The aim of the Department was to demonstrate to industry the usefulness of research with the thought that government aid would be withdrawn once the demonstration was made. About half the country's industry—principally the new industries—subscribed. Research associations were formed within various industries and research activities were financed by the joint contribution, pound for pound, of government and industry. Estimates of accomplishment from such research cannot be checked satisfactorily, but specific results have been achieved, and in one report enormous returns were claimed from total annual expenditures—of the order of 800 percent. It is perhaps significant that after careful study, industrial associations were considered the best means of providing subsidy, of demonstrating the value of research to industry unfamiliar with it, and of giving aid throughout industry. Even with such close contact with industry, there exists the same difficulty reported for the subsidy of agricultural research in Great Britain—

> . . . There are, however, some live farmers who make constant use of the facilities placed at their disposal by the State, with the result that the race is more than ever to the swift and intelligent. It is still unfortunately true that the very farmers who would benefit most from the help of the research workers are those who

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[12] See footnote 10.

[13] Cooper, Franklin S. Location and extent of industrial research activity in the United States. This volume, figure 46, p. 176.

[14] Bernal, J. D., F. R. S. The social function of science. New York, The Macmillan Co., 1939, p. 65, etc.

[15] Report of the advisory council—1932–33. Department of scientific and industrial research. Report for the year 1932–33. London, His Majesty's Stationery Office, 1934, p. 7.

are not being reached by the present methods of spreading scientific knowledge about farming.

In foreign laboratories, there has been greater secrecy, apparently, than in the United States, with a probable corresponding reduction in over-all efficiency. In some totalitarian countries ability to assign a considerable number of investigators to an individual problem may offset partially such inefficient policies, and such ability is of special significance in areas of technology where the fundamental creative work has been done and where applications are required that depend more upon training and experience than upon the creative ability of skilled research scientists.

One practice reported as tried in Soviet Russia has interesting possibilities. If a research man shows outstanding ability in a particular field the government may build him a laboratory, equip it well, and provide a staff of as many men as can be used. Incidentally, the staff and even the mechanics and all the helpers are understood to have their say in the choice and conduct of the program.

The Soviet Union has also attempted coordination of research on a grand scale. In one instance 18 large laboratories submitted plans for research in the chemistry of solid fuels (coal), and after study by a centralized body, assignments were distributed and financing guaranteed for 180 projects. An American coal scientist reports use there of excellent equipment, capable research leaders, and well-organized general scope of activity. He was especially impressed by the mass of technical data being compiled on the nature of the fuel resources.

"Men in Research"

Chemists dominated the early industrial laboratories and even now approximately 25 percent of industrial laboratory men have specialized in chemistry. Opinions differ as to whether this dominance has been due to the nature and scope of the science or whether research going on within the science developed interest and skill in the use of the research method. There is also some uncertainty as to whether the flow of technically trained men into industry brought research with it, or whether the demand of industry led to the great expansion of chemistry, chemical engineering, and other technical courses. One of the first of the great industrial laboratories started without a physicist, though the industry was based on physics. A similar situation originally held in other industries—the research director of a great steel company was trained as a chemical engineer, not a metallurgist; the research directors of the early food laboratories had little training in biological subjects. Other disciplines are gaining recognition, however. In one outstanding example, physicists formed the American Institute of Physics and made intensive effort to present the possibilities of applied physics to industry. The number of industrial physicists in the laboratories has increased significantly, and there is gradually increasing recognition of biologists, mathematicians and men trained in other disciplines, including the several divisions of engineering.

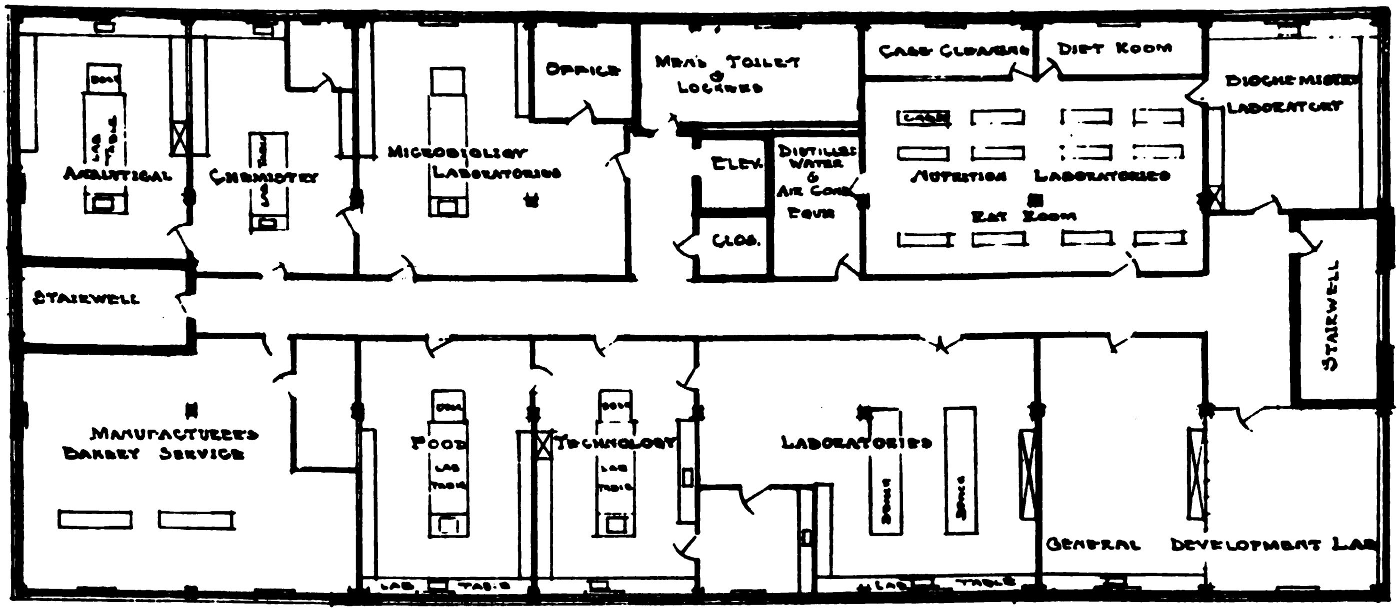
"Chemistry in Industrial Research" presents the most mature of the research disciplines. As such it speaks in part for other disciplines in a discussion of origins of research programs and to some degree their conduct. At the other extreme of acceptance by industry, however, are the biologists. From the results of the investigation made and reported in the study by Dr. E. B. Fred and Dr. C. N. Frey, there is reason to believe that opportunity exists for tremendous increases in the number of biologists, in the food industries particularly. It was found, however, that some changes in the teaching of applied biology in the universities for this purpose are desirable.

In the more highly developed laboratories, mathematics is beginning to find its special place. It would seem probable that with the extension and refinement of research method and policy there will be increasing dependence upon mathematics. This may be true particularly as more obvious research opportunities become exhausted by relatively simple and crude approaches. Dr. Thornton C. Fry, speaking for the profession, states that no university offers a complete and satisfactory curriculum in applied mathematics. He has made the definite recommendation that such a course be organized and offered by one of the universities. His present estimate of a very few graduates of such a course per year is of course no measure of the possible significance of such a step.

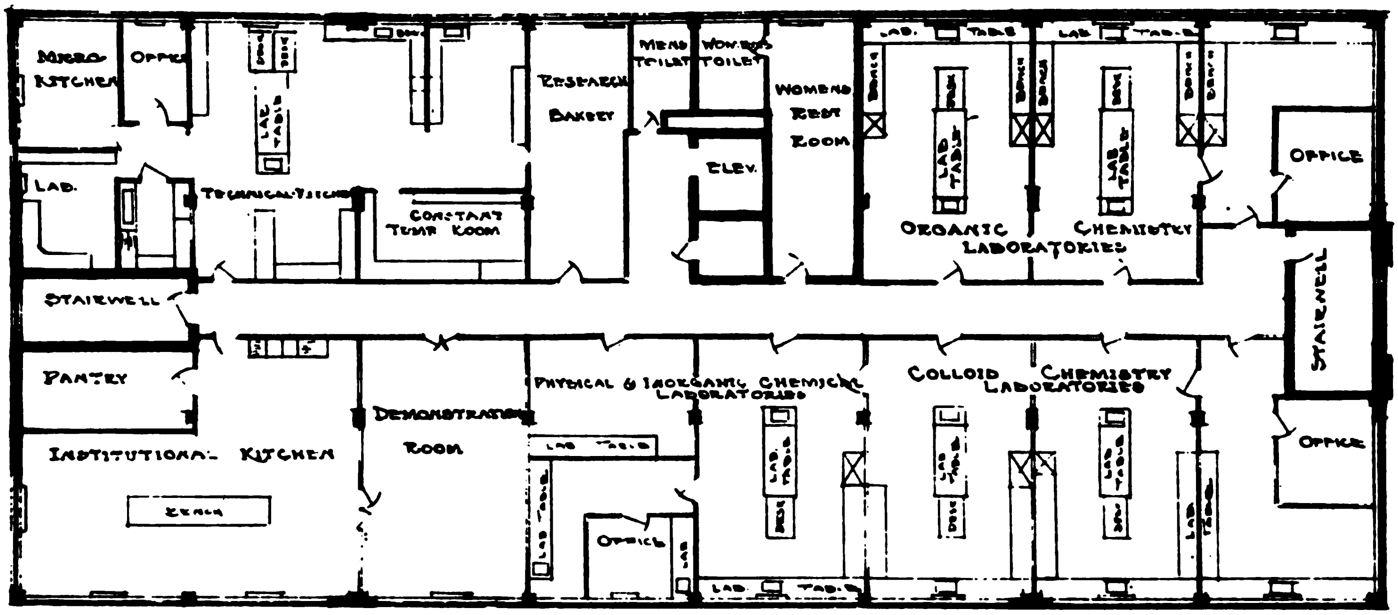
Of the various professional societies actively interested in research, the American Society of Mechanical Engineers has one of the most highly developed programs under its own auspices. Activities in cooperation with this Survey are being made the basis for a reconsideration of the research of the Society. It is well to note that mechanical, electrical, and other engineers are playing increasingly important parts in research as contrasted with straight engineering. In some of the larger machinery laboratories, for example, engineers predominate with possibly a few physicists and a few or no chemists.

From the duplication apparent in the report of various applied sciences and particularly from the study of border-line zones, it will be noted that the lines of demarcation between the various pure and applied sciences have begun to disappear and in some instances are quite obliterated. There remain, however, many areas, particularly on the fringes of the various sciences, that have not been developed satisfactorily. A few companies have surveyed their special branches of science and have established fundamental research to develop neglected areas. The areas are chosen either because current developments need new data or because of promise of new developments within the company's commercial and technical scope. The study of polymers by du Pont, of acoustics by Bell Telephone Laboratories, of aliphatic organic compounds by the Carbide and Carbon Chemical Company have been made for one or both reasons. But no organization now has responsibility and support for a search of the whole of science for neglected areas most promising in their ultimate return. If new industries are to come from research, as nylon, sound moving pictures, and new chemicals came from the investigations cited, fundamental studies in fields now comparatively neglected would seem to offer one of the best opportunities.

One of the most apparent of neglected areas is in



THIRD FLOOR PLAN



SECOND FLOOR PLAN

FIGURE 5.—Research Laboratory Floor Plan, General Foods Corporation, Hoboken, New Jersey

the great border line between the physical and social sciences, and some of the most interesting work is being done within it. Fatigue, for example, is a major factor in all industry, yet little is known about it. The National Research Council several years ago established a Committee on Work in Industry which is investigating the possibilities of clinical-type studies in this border line field. Limited industrial investigations have been made and they indicate rather remarkable possibilities. But possibly more important is the relation between scientist and layman. Where lies the responsibility for adjustment of industry and society to advances made by the research scientist? The scientist himself is the first to indicate that he is not too well qualified outside his field, and the average physical scientist has no great opportunity for developing, by experience, ability to deal with social problems. To say that physical scientists should solve the social problems they create is to speak without considering their concentrated devotion to their own particular contribution to human welfare. There is recognition, however, among some scientists that more attention may profitably be given to the social aspects of science, and insofar as their efforts contribute to a better understanding of science by laymen, and insofar as they help develop a liaison between technical man and layman, benefit is achieved. Some leaders among nontechnical men, especially in government and industry, have developed active lay interest in scientific and technical matters, and such development is probably even more beneficial and promising. The industrial executive, political leader and publicist are all in a position to assist in the adjustments that will continue to be necessary as research advances.

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SECTION II
RESEARCH IN THE NATIONAL ECONOMY

Contents

Contents—Continued

SECTION II

1. THE DEVELOPMENT OF INDUSTRIAL RESEARCH IN THE UNITED STATES

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ABSTRACT

In the nineteenth century the activity of scientists in Europe and the United States greatly increased man's fundamental knowledge. Laymen in this country, convinced of the importance of the newly discovered facts, made it financially possible to establish schools of science and technology, whose avowed object was to instruct students in the application of science to the everyday purposes of life.

Certain factors, however, served to delay the progress of applied science in this country. Its territory was so vast and its resources were so abundant that industry, for some time, was not particularly concerned with producing goods economically and efficiently. As long as the products of industry could be sold at a profitable price to a rapidly increasing population, the manufacturer had little incentive to invest his funds in the search for new methods or new products. It was not until the last quarter of the nineteenth century that competition became sufficiently severe to cause industrialists to turn with increasing frequency to professors in the universities and to commercial chemists for assistance. The results were so satisfactory that the gap between" pure" and applied science gradually closed, and trained chemists, physicists, metallurgists, and biologists found employment in industry. Also during this period, independent investigators, working in their own laboratories, made discoveries which resulted in the foundation of new industries and demonstrated further the advantages to be gained from utilizing in industry the facts and methods of science.

Until the twentieth century, however, industrial research remained largely a matter of the unorganized effort of individuals. Early in the 1900's a few companies organized separate research departments and began a systematic search not only for the solutions to immediate problems of development and production, but also for new knowledge that would point the way for the future.

The First World War focused the attention of the general public upon the accomplishments of applied science and greatly stimulated the growth of industrial research. Between 1920 and 1940 the number of industrial research laboratories increased from about 300 to more than 2,200.

Great changes have been wrought by the results of industrial research. More efficient and economical methods have conserved our resources; new materials have made possible better products; and new products have contributed to the health, pleasure, and comfort of the general public. Such changes have not taken place without some temporary misfortunes. Here and there industries have disappeared and people have been temporarily thrown out of work, but the net result of 40 years of organized industrial research in this country has been the enrichment of life to an incalculable degree.

The last section of this paper presents historical sketches of more than 50 industrial research laboratories.

Factors Affecting the Development of Industrial Research

The nineteenth century was nearly over before the industrial research laboratory became an important factor in the economic life of the United States. Not until the nineties had the developments in science, education, and industry reached the point at which the organized application of science to industry by trained men seemed to industrialists to be the key to greater progress and profit. Without a fund of scientific knowledge from which to draw and without a supply of men sufficiently prepared to apply that knowledge, the industrial research laboratory could not exist. By the end of the nineteenth century both of these requirements had been met, and in addition industry had come to realize, from the accomplishments of the works chemist and the individual experimenter, that many of the problems which defied rule-of-thumb methods would yield to the application of science. Today the research laboratory is widely recognized as an indispensable part of the country's industrial equipment. From it comes the knowledge that leads not only to improved methods and materials but also to entirely new processes and products and occasionally to new industries.

Progress in Chemistry and Physics in the Nineteenth Century

Scientists of the nineteenth century, building upon the solid foundation laid by those of the seventeenth and eighteenth centuries, uncovered and explained secrets of nature which, when applied to industry, were to alter completely the details of man's existence. Inquiring minds were active in many subjects, but a brief mention of a few men working in chemistry and physics is sufficient to show how important this period was for the future development of numerous great industries.

In 1801 Thomas Young brought before the Royal Society in London "the first convincing proof . . . that light is not a corporeal entity, but a mere pulsation in the substance of an all-pervading ether." It was in 1801 also that Sir Humphrey Davy, as lecturer and professor of chemistry at the newly established Royal Institution in London, was carrying on the experiments in electrochemistry by which he was able to isolate potassium and sodium and to prove that substances formerly considered elementary were really compounds. At the same time John Dalton was formulating his atomic theory, which, when first presented in 1803 before the Literary and Philosophical Society of Manchester, made little impression.[1]

The atomic theory was soon to receive some support, however, from the work of a French chemist, Gay-Lussac, who, in publishing his observations, brought out "the remarkable fact that gases, under the same conditions of temperature and pressure, combine always in definite numerical proportions as to volume."[2] An Italian, Amadeo Avogadro, quickly supplied the explanation of Gay-Lussac's observations in terms of the atomic theory, but because of the slow acceptance of the theory itself, Avogadro's law was neglected by chemists for a whole generation. Johan Jakob Berzelius, a Swedish chemist, however, put the theory to test in his laboratory by determining the combining weights of the different elements, and in 1818 he published his first table of atomic weights.

Ten years later the barrier between animate and inanimate nature was destroyed when a young German chemist, Friedrich Wöhler, succeeded in synthesizing urea in his laboratory; and in 1831 Michael Faraday, Davy's protégé and successor at the Royal Institution, opened the whole field of electricity and magnetism for cultivation by such men as Hermann von Helmholtz, Clerk Maxwell, and Heinrich Hertz.

Perhaps the greatest of all the chemists of the period was Justus von Liebig, whose laboratory, established at Giessen in 1824 for research in organic chemistry and agricultural chemistry, became the training school for young chemists from all countries. When called to Munich in 1852, he developed there a still larger laboratory to which came a steady stream of applicants seeking the privilege of studying and working with the renowned teacher; among them were the Americans, Eben Horsford, J. Lawrence Smith, Frederick A. Genth, Wolcott Gibbs, and C. M. Wetherill.

Just before the middle of the century Louis Pasteur began the work which was to mean so much first to French industry and later to all mankind. Three advances of far-reaching importance came toward the end of the century, when J. J. Thomson isolated the electron and measured its charge and mass; when Röntgen discovered X-rays; and Becquerel observed the first indications of radioactivity.

Two scientists in the United States also made distinct contributions to scientific theory. The first was Josiah Willard Gibbs, who in 1876 presented his phase-rule, one of the most important additions to the theory of chemistry made by an American. Partly because it was not sufficiently brought to the attention of chemists and partly because its mathematical presentation was not at first understood, a decade passed before it was applied. The second was Joseph Henry who, although preceded by Faraday in the announcement of the theory of current induction, was the first to announce the phenomenon of self-induction.

Foundation of Schools of Science and Technology

The reservoir of scientific knowledge was filling, and, as it filled, many men turned their thoughts to means by which this knowledge could be utilized. As in the discovery of new facts, so also in the application of them, the countries of Europe quite naturally preceded the United States. Special schools were founded where students could learn not only scientific theories but also their application to industry. Germany, France, and, to some extent, England had recognized that "the greatest warfare of the nineteenth century is industrial warfare—the struggle between great nations for supremacy in the various industries, and for the control of the various markets."[3]

Many of the early technical schools grew out of the industrial demands of the locality in which they were established. The silver mines of Freiberg, for example, led to the founding in 1765 of a famous School of Mines,

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[1] Williams, Henry Smith. The story of nineteenth-century science. New York, London, Harper and Bro., 1900, p. 255.

[2] The story of nineteenth-century science, pp. 256–257. See footnote 1.

[3] White, Andrew D. Scientific and industrial education in the United States *Popular Science Monthly*, *5*, 172 (1874).

which is said to be the oldest technical "High College" in the world. It had a faculty of eminent men and was a center of activity in geology, mineralogy, crystallography, metallurgy, and chemical technology.[4] The Royal Polytechnic Institute at Dresden was started in 1828, and by 1845—

> there were in all Germany, including Austria, thirty polytechnic schools, usually one and sometimes two in each large city; . . . forty-six schools of agriculture, seven schools of mines, and eighteen schools of forestry. . .[5]

The German states came early to realize that their material prosperity was dependent largely upon the thoroughness of their systems of scientific education.

In supplying instruction in chemistry, France, however, was far ahead of other countries. "Våuquelin was the first to organize a course of instruction in his small laboratory for students anxious to learn, while Gay-Lussac and Thénard also taught in their laboratories, which however were exceedingly cramped."[6] French schools such as the Polytechnic School, the School of Engineering, the School of Mines, and the great Central School of Arts and Manufactures were training students in the nineteenth century to apply the new scientific knowledge.

The movement was not so far advanced in England, and in 1868, after a survey of the schools and universities on the continent, Matthew Arnold wrote:

> In nothing do England and the Continent at the present moment more strikingly differ than in the prominence which is now given to the idea of science there, and the neglect in which this idea still lies here. . .[7]

In the United States an interest in science, particularly chemistry, was developing during the first half of the nineteenth century. In 1802 Benjamin Silliman was appointed professor of chemistry at Yale and immediately granted a leave of absence "in order that he might acquire the necessary knowledge and experience." At that time Philadelphia was the center of scientific activity and without question the best place in the country at which to gain a knowledge of chemistry. Benjamin Rush had been teaching chemistry in the Philadelphia Medical School since 1769.[8] James Woodhouse and later Robert Hare also taught chemistry at the Medical School of the University of Pennsylvania, and it was from a close friendship with the latter that Benjamin Silliman gained much of the knowledge and experience which made it possible for him to develop the subject of chemistry at Yale. Others were struggling to get chemistry recognized as a worthy subject in the college curriculums: Aaron Dexter and John Gorham at Harvard; Nathan Smith, Lyman Spaulding, and James Freeman Dana at Dartmouth.

In 1845, however, even the most advanced colleges and universities still placed most of their emphasis upon the classical studies, and what little instruction they offered their students in the physical and natural sciences was elementary in character and confined to undergraduates, for the graduate student was, as yet, practically unknown. Instruction was limited to a textbook and lectures during which the professor performed a few demonstrations. Laboratories, as we know them today, did not exist, and anything approaching laboratory work by students had scarcely been thought of. In fact few of the professors holding chairs in the sciences possessed the necessary equipment or had the necessary rooms for such experimental work. A brief description of Robert Hare's laboratory, one of the best of that day, will give some idea of what a chemist in the 1830's had to work with:

> The hearth behind the table, is thirty-six feet wide, and twenty feet deep. On the left—is a scullery supplied with river water by a communication with the pipes proceeding from the public water works, and furnished with a sink and a boiler—. In front of the scullery are glass cases for apparatus. On the right of the hearth are two other similar cases. . . . Behind the lower one of these is the forge room, about twelve feet square; and north of the forge room are two fireproof rooms communicating with each other, eleven feet square each; the one for a lathe, the other for a carpenter's bench, and a vice bench. Over the forge room is a store room, and over the lathe and bench rooms is one room of about twenty by twelve feet. In this room there is a fine lathe, and tools. The space—to the right is divided by a floor into two apartments—. The lower one is employed to hold galvanic apparatus, the upper one for shelves, and tables, for apparatus, and agents, not in daily use. In front of the floor just alluded to is a gallery for visitors.
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> The canopy over the hearth is nearly covered with shelves for apparatus, which will bear exposure to air and dust, especially glass. In the center of the hearth there is a stack of brick work for a blast furnace, the blast being produced by means of very large bellows situated under one of the arches supporting the hearth. The bellows are wrought by means of a lever and a rod descending from it through a circular opening in the masonry.
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> There are two other stacks of brick work on the hearth against the wall. In one there is a coal grate which heats a flat sand bath, in the other there is a similar grate for heating two circular sand baths, or an alembic. In this stack there is likewise a powerful air furnace. In both stacks mentioned, there are evaporating ovens—.[9]

The idea of a special school of science or of a technical school in which the applications of scientific discovery might be stressed grew slowly at first, and naturally so, for its successful development demanded the evolution of methods of instruction which often violated accepted

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[4] Chittenden, Russell H. History of Sheffield Scientific School of Yale University, 1846–1922. New Haven, Yale University Press, 1928, vol. 1, pp. 14 and 20.

[5] See footnote 4.

[6] Meyer, Ernst von. A history of chemistry. New York, Macmillan and Co., 1891, p. 524.

[7] Arnold, Matthew. Higher schools and universities in Germany. London, Macmillan and Co., 1874, p. 212.

[8] Newell, Lyman C. Chemical education in America from the earliest days to 1820. *Journal of Chemical Education*, *9*, 680 (April 1932).

[9] *The American Journal of Science and Arts*, *19*, 26–27 (January 1831).

tradition.[10] Nevertheless there were some men ready to give of their wealth to establish such schools, for they sensed the great possibilities of the future if only the rapidly accumulating new knowledge could be made available to those who would find their work in industrial enterprises. Stephen Van Rensselaer was one of the first of these men. For generations his family had ruled over a vast feudal estate that included all the land now comprising Albany, Columbia, and Rensselaer counties. Although the family's estate was greatly reduced and its baronial rights were lost upon the establishment of the colonial government during the American Revolution, there still remained a large property which Stephen Van Rensselaer undertook to develop after his graduation from Harvard College. He was the first to propose a canal connecting the Hudson river with the Great Lakes and, as chairman of the canal commission, engaged Prof. Amos Eaton in 1821 to make a geological survey of the proposed route of the canal from Albany to Buffalo.[11] The importance of the work and the difficulty of finding men who were qualified to conduct it so impressed Van Rensselaer that he was convinced of the need for providing men with training in science and technology.

In 1824 Van Rensselaer wrote to Reverend Samuel Blatchford:

> I have established a school in the north end of Troy, for the purpose of instructing persons . . . in the application of science to the common purposes of life. My principal object is to qualify teachers for instructing the sons and daughters of farmers and mechanics . . . in the application of experimental chemistry, philosphy and natural history to agriculture, domestic economy, the arts and manufactures.[12]

Professor Eaton, whose interest in science had taken him to Yale to study with Benjamin Silliman and whose ability for making popular presentations of scientific discoveries had led Governor De Witt Clinton in 1818 to invite him to give a course of lectures before the members of the New York legislature, was to hold the office of "senior professor" and teach chemistry and experimental philosophy.[13] Students were not to be taught according to the usual method by seeing experiments and hearing lectures, but by lecturing and experimenting in turn under the guidance of a competent instructor. Thus by a term of labor, like apprentices to a trade, they were to become operative chemists.[14] The Rensselaer School opened on January 3, 1825, and for 17 years, under Professor Eaton's direction, it offered a year course of study. About 1850 the emphasis was shifted to civil engineering, and the course of study was lengthened to three years.

The year 1846–47 was an important one in the history of education in the United States. The Yale Corporation resolved to organize a school of applied chemistry and by their action founded what later came to be called the Sheffield Scientific School in honor of its first large donor, Joseph E. Sheffield, cotton merchant, promoter of railroads and canals. That same year the catalog of Harvard College carried the announcement:

> In the course of the winter of 1846–47, arrangements were made by the government of the University for the organization of an advanced School of Science and Literature—to be known and designated as the Lawrence Scientific School in the University at Cambridge.

Like Sheffield, Abbott Lawrence was a successful merchant and manufacturer interested in education and willing to give money to provide a scientific training which the existing departments of the University did not offer.

Also in 1846 William Barton Rogers, professor of natural philosophy at the University of Virginia, wrote to his brother Henry of his feeling about the idea of establishing in Boston a Polytechnic Institution, "whose true and only practicable object" should be "the inculcation of all the scientific principles which form the basis and explanation of (the arts)" and with this a "full and methodical review of all their leading processes and operations in connection with physical laws."[15] Of all places in the world Rogers felt that Boston was the one "most certain to derive the highest benefits" from such an institution because of "the knowledge seeking spirit and the intellectual capabilities of the community." He felt that in Boston "the occupations and interests of the great mass of the people were immediately connected with the applications of physical science, and their quick intelligence had already impressed them with just ideas of the value of scientific teaching in their daily pursuits."[16] Although Rogers never lost opportunity to advance his ideas and plans for a Polytechnic Institute, it was 15 years before Governor Andrew approved an "Act to Incorporate the Massachusetts Institute of Technology," one branch of which was to be a School of Industrial Science that would provide a "complete course of instruction and training, suited to the various practical professions—and, at the same time, meet the more limited aims of such as desire to secure a scientific preparation for special industrial pursuits . . . having their founda-

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[10] Butler, Nicholas Murray, Editor. Education in the United States. Mendenhall, T. C. Scientific, technical and engineering education. Albany, N. Y., J. B. Lyon Co., 1900, Monograph No. 11, p. 3.

[11] Education in the United States, p. 6. See footnote 10.

[12] Rensselaer Polytechnic Institute, *Bulletin*, 7 (March 1940).

[13] Scientific, technical and engineering education, p. 7. See footnote 10.

[14] Scientific, technical and engineering education, p. 8. See footnote 10.

[15] Rogers, William Barton. Life and letters of William Barton Rogers. Edited by his wife. Boston, New York, Houghton Mifflin and Co., 1896, vol. 1, p. 260.

[16] Life and letters of William Barton Rogers. See footnote 15.

tion in the exact sciences."[17] By 1899 the Institute had graduated nearly 2,000 men.

Before the middle of the century the vast mineral resources of the country had scarcely been touched, and the need for trained men to discover and develop them was great. At Columbia College, the efforts of Professor Thomas Egleston, a graduate of Yale and the *École des mines* in Paris, resulted in 1864 in the organization of the School of Mines. Although Columbia College did not pledge itself to support the new school, it did permit the use of some rooms in the college buildings. George T. Strong, William E. Dodge, Jr., and several others provided about $3,000 to equip the laboratory. The members of the instructing staff, consisting of Professor Egleston and a little later Professors Charles F. Chandler and F. L. Vinton, were appointed without salary, for they were expected to gain their livelihood from fees.[18]

Although originally intended to train mining engineers, the school soon had on its staff men qualified to teach in other fields, and the program of the school was expanded to include civil engineering, applied chemistry, sanitary engineering, geology, and architecture. A year after its opening the School of Mines became a coordinate branch of the college, and for some time brought to it much of its fame.[19]

In Worcester, Mass., two men, Mr. John Boynton, a merchant, and Mr. Ichabod Washburn, founder of the Washburn and Moen steel and wire manufactory, had confided to the Reverend Seth Sweetser their desire to contribute to the establishment of a school for training young men for industrial pursuits. A conference with several other individuals interested in such a school resulted in a united effort from which came the opening of the Worcester Polytechnic Institute in 1868. Dr. Charles O. Thompson, its first president, is said to have gained from a study, particularly of the Imperial Technical School at Moscow and the Institute of Technology at St. Petersburg, the idea of combining lectures and the study of textbooks with practical exercises in workshops where the student could learn the construction and use of machines.[20]

Other businessmen active in the development of our natural resources provided opportunities in their respective localities for young men to get a practical education. Asa Packer, tanner, carpenter, owner and master of canal boats, mines, and railroads made it possible to found Lehigh University. Edwin A. Stevens, one of the earliest users of steam for water transportation, provided by his will the original funds for Stevens Institute at Hoboken. Before 1900 other generous donors had provided for such institutions as the Case School of Applied Science, at Cleveland; the Rose Polytechnic Institute at Terre Haute, Indiana; Throop Polytechnic Institute, later to become the California Institute of Technology; and the Armour Institute of Technology at Chicago.

The long-established colleges and universities could not neglect the science and technology which was spreading rapidly and affecting so markedly the development of the country. The schools of science at Harvard and Yale have already been mentioned. Dartmouth, University of Pennsylvania, Princeton and many other institutions added schools of science during the nineteenth century even though "the student preparing for an industrial profession was not considered as of the same caste with the student preparing for a 'learned profession' "[21]

A major event affecting the development of scientific and technical education in the United States was the act, proposed by Justin S. Morrill, of Vermont, and passed by Congress in 1862, providing for the issuance to every state of scrip for 30,000 acres of land for each representative and each senator sent to Congress by that state. The scrip was sold in the open market, usually for low prices, and the proceeds spent particularly to found or assist institutions in which subjects relating to agriculture and the mechanic arts should be leading branches of study. Classical and scientific studies were not to be excluded, however, and the study of military tactics was definitely included. Some states gave their funds for the endowment of scientific and industrial education in an existing institution; others founded purely agricultural colleges; and still others founded separate schools which have since grown into great institutions. Purdue, Pennsylvania State College, the Universities of Illinois and Ohio are but a few of those organized under the terms of the Morrill Act. Andrew D. White, a vigorous proponent of the "new education," pointed out the significance of this act in 1874, when he said:

> It was to provide fully for an industrial, scientific, and general education suited to our land and time—an education in which scientific and industrial studies should be knit into its very core, while other studies should also be provided for.[22]

Vast Natural Resources

Although the amount of scientific knowledge was increasing and more and more men were being taught

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[17] Life and letters of William Barton Rogers. See footnote 15, vol. 2, p. 223.

[18] Resignation of Professor Chandler. *Metallurgical and Chemical Engineering, 8,* 66 (February 1910).

[19] See footnote 18.

[20] Scientific, technical and engineering education, p. 13. See footnote 10.

[21] Scientific and industrial education in the United States, p. 171. See footnote 3.

[22] Scientific and industrial education in the United States, p. 173. See footnote 3.

in schools of science and technology to apply it, obstacles still existed to delay the application of science to industry.

When the nineteenth century opened, our ancestors had before them a country whose limits they did not know, but one which was soon to yield them seemingly inexhaustible natural resources. As the population increased in the United States, more and more attention was given to the development of manufactures, although the obstacles to their introduction were numerous and troublesome. In time, canals, railroads, and steamboats made available the great deposits of ore and coal and widened the areas of profitable trade. This expansion of transportation facilities was made possible by feats in civil and mechanical engineering that, for the age, were "gigantic." Our dependence upon foreign-trained engineers was soon relieved, and in some branches of engineering we began to set the example for Europe. The "captains of industry" were bold and capable; masters of organization and of men. Their immediate problems were not those of producing efficiently and economically, but rather those of acquiring control of resources, transporting materials, and finding an adequate supply of labor to manufacture them into products for which a greedy and growing population was clamoring. Technical improvements were imported from Europe and quickly adapted to the requirements of industry. Until the last quarter of the nineteenth century, however, technical progress was based far more upon inventive experimentation and trial-and-error methods then upon a conscious and systematic effort to apply the principles of science to industry through the medium of research. In no way does this fact belittle the achievements of those who utilized such methods, or serve as a criticism of industrial leaders of that era. It simply indicates that industry had not yet reached the point where a further increase in wealth depended upon the "progress of scientific knowledge and the refinement of engineering skill." As long as there was a large demand at a profitable price for the products of the mill and factory, owners and managers had little incentive to invest even a small portion of their earnings in a search for new methods and new products. When, even under such generous natural conditions, problems did arise which threatened profits, the industrialist's traditional attack was a plea for greater tariff protection, or a "proposition" which would offset the wasteful methods of production by eliminating the offending competitor.[23]

The Protective Tariff

As late as 1913 an editorial in the Journal of Industrial and Engineering Chemistry went so far as to say that probably the greatest factor in retarding the development of scientific research among our industries has been a high tariff; that it has caused prosperity and enormous profits in spite of short-sighted management; and that political research has been well understood. Many industrial managers have spent thousands on the lobby and not a cent for placing their business on a sound scientific footing . . . Only after hope of increasing profits by the political route has been entirely eliminated, will they turn to the scientific method.[24]

Although this is probably an overstatement of the effect on research of high tariffs, it is true, particularly in the early days of our development, that they frequently deprived the United States of the opportunity to share in the benefits of improvements which had been made abroad. For nearly 30 years, for example, the domestic producers of hammered iron were protected from the rolled iron which Great Britain was producing much more cheaply under Cort's new processes of puddling and rolling.[25] Moreover, tariff protection and industrial combinations undoubtedly tended to hide problems, or at least to hide the importance of problems, and in so doing postponed a scientific attack upon them. On the other hand, the tariff undoubtedly made it easier for many industries to become established, and the combination of small industrial units into large corporations made it possible for the latter to support costly research.

Attitude of Industrialists and Scientists

The industrialist's suspicion of the scientist and the scientist's disdain for the man who would apply his discoveries to everyday enterprises also delayed research. To the manufacturers, industry was no place for the impractical dreamer; he belonged in the university, where he would not upset the methods that had worked for many years. "Even the trained chemist," said Willis R. Whitney in 1916, "constituted in the minds of most manufacturers a pure speculation." This feeling was partly the result of ignorance of what a properly trained man could accomplish and partly the result of the numerous failures of men who were employed to do research although they were wholly unqualified through temperament and lack of proper training and resourcefulness to undertake it. The manufacturer, frequently unwilling to provide the necessary conditions and equipment for research, expected immediate and startling results. Speaking of this attitude as he observed it in the oil industry, Mr. William M. Burton said:

> It is very curious that from the early days of the industry until the discovery of Lima oil, there seems to have been prejudice on the part of practical oil men against the chemical fraternity.

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[23] Duncan, R. K. Temporary industrial fellowships. *North American Review, 185,* :54 (May 3, 1907).

[24] Research. *Industrial and Engineering Chemistry, 5,* 966 (December 1913).

[25] Taussig, F. W. The tariff history of the United States. New York, London, G. P. Putnam's Sons, 5th ed., 1909, p. 127.

> Why, . . . is not entirely clear, but I think one reason might be the fact that manufacturers frequently called upon chemists of general training to solve some particular problem connected with their business, ignoring the fact that the chemist probably had had no practical refining experience. The chemist, therefore, probably offered suggestions which were totally impracticable and the manufacturer seeing the fact, was not particularly impressed with the chemical profession as a possible aid to his business . . .[26]

The scientist, on the other hand, was not eager to see his discovery applied to industry. He was in search of truth, and the application was unimportant. Here and there a scientist could be found who went so far as to feel that "making a utility of the God-given discoveries of the truly beautiful phenomena of Nature was a prostitution to be deprecated, and that research could only be pure when it was 'sterile.' "[27]

In time, however, the gap between "pure" and "impure" science was to become much smaller. As William H. Walker expressed it:

> There is with scientific men a general awakening to the fact that the highest destiny of science is not to accumulate the truths of nature in a form that no one but the elect few can utilize, but that the search for truth can be combined with a judicious attempt to make the truth serve the public good. Thus the distinction which has existed between the terms pure science and applied science is rapidly falling away. An attempt to define these two kinds of science reveals the fact that their distinction is a general impression rather than a clear statement.[28]

Period of Unorganized Research

The wealth of natural resources, the reliance upon tariff protection, and the mutual distrust of the scientist and the industrialist served to delay but failed to prevent the infiltration of science into industry. Growing competition within home industries could not be met with high tariffs, and combinations seldom achieved a monopoly. Obviously, a new attack upon industrial problems was necessary, and farsighted, technically-minded leaders gradually overcame the objections of their associates and made it with applied science. They turned to the university professors and the commercial chemists for assistance and advice upon certain specific problems. With many misgivings, they added to their staffs trained chemists whose first work was largely restricted to testing, sampling, and controlling processes. It was not long, however, before these chemists, with their special training, substituted scientific methods for rule-of-thumb and, as a result, not only accelerated the improvement of existing processes but also utilized waste products and created new products. Many a research laboratory has evolved from the dingy corner allotted to a plant chemist.

Early Plant Chemists

An early and isolated example of such a laboratory was that of the Merrimack Manufacturing Company at Lowell, Mass. From 1834 until his death in 1868, Samuel Luther Dana served the company as resident and consulting chemist.[29] After being graduated from Harvard College in 1813, he studied medicine and became an M. D. in 1818. For 8 years he practiced in Waltham, but the subject of chemistry had a fascination for him, and even before he gave up his medical practice he had "established a laboratory for the production of sulfuric acid and bleaching salts." This enterprise was soon merged with the Newton Chemical Company and Dr. Dana served it as superintendent and chemist until 1833. He then went to Europe for a year and upon his return became chemist for the Merrimack Manufacturing Company. Possessed of a wide knowledge of substances and an originality in devising means for solving problems, he undertook a systematic study of the action of the dung of beeves which at that time was used "for removing the excess of mordant in printing calicoes with madder." This research led to the discovery that "crude phosphates in a bath with bran" were a complete substitute for the expensive and unpleasant material which had hitherto been indispensable. By using sodium phosphate made from bones, Dana greatly improved the process of calico printing in the United States. Later, Mercer found that arsenates were equally effective and cheaper.

Dana continued his study of the chemical changes that took place in the process of bleaching cotton fabrics preparatory to printing them and finally developed what became known as the "American System" of bleaching, once referred to by the French scientist Persez as realizing "the perfection of chemical operations." The process was not only widely adopted in the industry, but was also highly praised as a piece of scientific investigation, a description of it being published in the *Bulletin de la Société Industrielle de Mulhouse* in 1838.

Although much of Dana's attention was given to the many diverse problems which arose in the mills, he went on year after year studying madder, its nature, and its application to both dyeing and agriculture. Moreover he continued his study of manures, and 1842 published *The Farmer's Muck Manual of Manures* which was considered "the sheet anchor of libraries in the rural districts of New England for many years." Benjamin Silliman, the younger, placed him first in point of "time, originality, and ability" among those in the United States who wrote upon scientific agriculture. To Dr. Dana should go the distinction of estab-

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[26] Burton, William M. Chemistry in the petroleum industry. *Industrial and Engineering Chemistry, 10,* 485 (June 1918).

[27] Whitney, W. R. Incidents of applied research. *Industrial and Engineering Chemistry, 8,* 561 (June 1916).

[28] Walker, W. H. Chemical research and industrial progress *Scientific American Supplement, 72,* 14 (July 1, 1911).

[29] This account of Dana's work is based upon those in Youmans, W. J. Pioneers of science in America. New York, D. Appleton and Co., 1896, pp. 313-315; Dictionary of American biography. New York, C. Scribner's Sons, 1930, vol. 5, p. 61.

lishing one of the first industrial research laboratories in this country—a laboratory in which he worked systematically for 34 years not only to solve the immediate problems of the Merrimack Manufacturing Company, but also to discover new facts which would aid the growing textile industry in New England.

Another pioneer chemist in industry was Charles Benjamin Dudley, who, in 1875, left his position as teacher of science at the Riverside Military Academy, Poughkeepsie, N. Y., to join the staff of the Pennsylvania Railroad.[30] At that time the company had acquired some apparatus for conducting physical tests, but had made no provision for making chemical analyses. Any need for the services of a chemist was met by consulting an outsider. When the company decided to have an engineering laboratory "in its broadest sense," a department of physical tests was easily organized from the staff and equipment already available. To organize a department of chemical tests, however, was not so simple, for nobody within the company had had the necessary experience, and no other railroad maintained a laboratory from which a trained man could be hired. Mr. Theodore N. Ely, the Superintendent of Motive Power for the Pennsylvania R. R., consulted his friend Dr. Coleman Sellers, and upon his recommendation offered the position to Dudley. Since the latter had a strong desire to make the study of "physiological chemistry his specialty," the decision to give it up for work in industry was not easily made. Moreover Dudley was well aware of the general antagonism and skepticism regarding the work of the scientist when any attempt was made to apply it to practical affairs. He knew too that the undertaking was largely an experiment the success of which would depend not alone upon the accuracy of his chemical analyses, but also upon his ability to cooperate with men who would have little use for his approach. In spite of these undesirable features, Dudley knew that the railroad would offer many new and interesting problems, and that the higher executives were men who would be sympathetic toward his efforts. He accepted the offer and began his work with the help of one or two untrained men.

The problem which confronted him was not a simple one. First of all he had to determine what material was best for the company to use for any given purpose. Once this decision was made, he had to prepare specifications that would insure the company's getting exactly what it wanted when purchasing in an open and highly competitive market. To get such results, a third step was necessary, that of devising "the best methods and the most efficient organization for carrying on routine acceptance tests on an extensive scale." And finally he had "to conduct independent research and keep in touch with the latest scientific and practical developments in a vast field" in order that the railroad might profit by any method or product that would increase its efficiency or reduce its operating costs.

At the time Dudley joined the staff of the Pennsylvania Railroad, the loss resulting from the rapid corrosion of valves and other parts of the locomotives was a serious one. He immediately began a study of the tallows used for lubricating the locomotive cylinders and found that by careful and proper rendering and by the selection of fresh tallow he could greatly reduce the loss. The next step was a carefully prepared specification which would govern future purchases of tallow.

A more dangerous situation, involving the safety of passengers, existed in connection with the railroad's signal lights, which frequently grew dim and sometimes failed entirely. An investigation showed that no trouble arose when lard oil made in the company's own oil house was used. Then Dudley experienced difficulties in his attempt to discover why lard oil purchased from dealers gave trouble. Almost by accident he discovered, in the course of his experiments, that "when acid was added to a mixture of cotton-seed oil and lard oil a reaction took place in which the heat evolved was in almost exact proportion to the cotton-seed oil." A conclusion was not difficult to draw: the manufacturers were mixing low-priced cotton-seed oil with high-priced lard oil and selling the mixture for pure lard oil. Notice that in the future the company would accept no lard oil that did not meet Dr. Dudley's tests brought immediate expressions of indignation, which, however, were quickly followed by an ample supply of pure lard oil.

An investigation of The Chemical Composition and Physical Properties of Steel Rails brought Dudley world-wide attention. Steel was being offered to the railroads as a substitute for iron, but nobody knew to what extent it would meet the requirements of actual service. Before beginning his investigation, Dudley spent a few weeks at the Sheffield Scientific School in order to learn more about the methods of analyzing steel. After his work at Yale, in an effort to discover the reasons for the variable life of steel rails, he examined 25 samples which in actual service had been rated from "good" to "very bad." His data, which consisted of the location of the rail, the tonnage carried over it, and the results of chemical and physical tests, pointed to the conclusion that mild steel made a rail which was less likely to break and which would wear longer than one of harder steel. On the basis of his findings he then recommended a formula for the chemical composition of rails that should be purchased in the future by the Pennsylvania Railroad.

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[30] This account of Dudley's work is based upon papers by Marburg, E., Ely, T. N., Smith, E. F., and Howe, H.M., published in a Memorial volume commemorative of The life and life work of Charles Benjamin Dudley, Ph. D. (American Society for Testing Materials.) Philadelphia, Pa., The Society, 1911.

Some of the leading steel producers took immediate issue with Dudley on the grounds that his experiments were inadequate, that his results were not consistent with the experience of other users, and that his formula would greatly increase the cost of producing steel rails. Nevertheless, Dudley had started an inquiry which led to many more researches, both in the United States and abroad.

An inkling of the significance of his work can be gained from a statement made by Capt. W. R. Jones, of the Carnegie Company, who had taken issue with some of Dudley's findings:

> Before he proposed this formula how many of those who condemned it as being egregiously wrong had any idea whatever of the relations of carbon, silicon, and manganese to phosphorus? Although Dr. Dudley may be wrong, and I believe he is only partially correct, yet he was the first to endeavor to establish a formula of this kind, and is therefore entitled to the thanks of steel makers; for although it may not be correct, it is much nearer the mark than what others have simply guessed at; and the direct results of his investigations have been to stimulate investigations by others and throw much light on a dark subject.[31]

Rails, axles, springs, paints, varnishes, coals, disinfectants, dyes, were all subjected to Dr. Dudley's analysis, and the results were practically expressed in standard specifications. Today much of the type of work which he did is no longer classified as research; for, because of his pioneer work and the work of the American Society for Testing Materials, organized largely through the efforts of Dr. Dudley, such tests and analyses have been standardized and no longer involve a search for the unknown. But in the seventies and eighties, when business men had little faith in what the chemist could do, and the chemist had little knowledge of what he could do for the business men, Dudley's work was true industrial research. When his career with the Pennsylvania ended, the laboratory which he had organized was staffed by 34 trained chemists and many assistants.

The rapid and spectacular developments in the American iron and steel industry would have been impossible but for the work of trained chemists, metallurgists, and engineers. If the industry as a whole has lagged in organized research, it is nevertheless true that some companies began early to "make a rational attempt to apply the findings of the chemist to their immediate problems."

In the spring of 1863 a chemical laboratory was established at Wyandotte, near Detroit, where a furnace had been built for experimenting on a large scale with the process for producing steel invented by William Kelly. Previously the experiments with the Bessemer process had not met with success largely because of the imperfect control of raw materials. Those in charge of the furnace at Wyandotte, however, recognized the necessity for using suitable pig iron and established laboratory facilities for determining the quality of the iron received from various furnaces.[32]

W. F. Durfee, the man who was invited by Capt. E. B. Ward to design and superintend the furnace at Wyandotte, made an interesting comment about this laboratory:

> It is quite certain that long after the establishment (of this laboratory) the manufacturers of steel in Sheffield did not regard the employment of chemical investigation of their materials or products as desirable or practicable. I have in my possession a pamphlet published in Sheffield, England, as late as 1870, for the purpose of attracting attention and trade, in which the following sentences occur: "The various articles on the manufacture of cast steel in the encyclopaedias and other works are for the most part out of date or are written by scientific men having little or no practical acquaintance with the subject and consequently are not of much value—The steel manufacturers of Sheffield are not chemists. The application of chemistry to the manufacture of steel has not yet met with any success. The analysis of steel is a very difficult process. It has frequently been attempted in Sheffield but never with any practical success."[33]

At the insistence of a number of the members of the American Iron and Steel Association, J. Blodgett Britton established in Philadelphia in 1866 an "Ironmasters' Laboratory" in order to "encourage the development of workable bodies of iron ore and to inform producers of the quantity and quality of the metal they would yield."[34]

Alloys also began to interest American iron-masters about this time.

> In 1868 four of the largest rail mills in the U. S. were experimenting with chrome ore and manganese in the puddling furnace for hardening rail heads, and the Government had ordered an experimental lot of projectiles to be made of chrome iron in order to test their ability to penetrate hardened armor.[35]

The first chemist in the iron industry employed by a company not making Bessemer steel is believed to have been with the firm of Kloman, Carnegie & Company, operators of the famous Lucy furnace.[36] Two developments seem to have convinced Henry Phipps, then in charge of the Lucy furnace, that the services of a chemist were necessary. Companies producing steel were beginning to state their requirements in chemical terms, "the principal one being that the metal should not contain more than ten-hundredths of 1 percent of phosphorus." For every increase of one-hundredth of

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[31] The life and life work of Charles Benjamin Dudley, Ph.D., p. 23. See footnote 30.

[32] Clark, Victor S. History of manufactures in the United States (1860–1893). New York, McGraw-Hill Book Co., Inc., 1929, vol. 2, pp. 70–71.

[33] Durfee, W. F. The first chemical laboratory. *American Iron and Steel Association, Bulletin 30*, 249 (November 10, 1896).

[34] History of manufactures in the United States (1860–1893), p. 78. See footnote 32.

[35] History of manufactures in the United States (1860–1893), p. 78. See footnote 32.

[36] Bridge, J. H. The inside history of the Carnegie Steel Company. New York, The Aldine Book Co., 1903, p. 65.

1 percent of phosphorus the companies deducted 25 cents per ton from the price they would pay.[37] Also at a critical period in the financial history of Kloman, Carnegie & Company, the Lucy furnace suffered a "chill" upon the substitution of high-grade Lake Superior ores for the low grade ores on which it had been running well. As a result the company hired Dr. Fricke, a German chemist, and in the words of Andrew Carnegie:

> . . . great secrets did the doctor open up to us. Iron stone from mines that had a high reputation was now found to contain ten, fifteen, and even twenty per cent less iron than it had been credited with. Mines that hitherto had a poor reputation we found to be yielding superior ore. The good was bad and the bad was good, and everything was topsy-turvy. Nine-tenths of all the uncertainties of pig-iron making were dispelled under the burning sun of chemical knowledge.[38]

While competitors described the expenditure for a chemist as an extravagance, Carnegie and his partners reaped substantial benefits from their knowledge of the composition of ores. They bought ore at low prices from mines which other furnace owners held in disrepute; they bought for 50 cents a ton the flue cinder from the heating furnaces and the roll scale from the mills, byproducts that competitors were piling on the river banks as waste, mixed them with smaller quantities of high-grade Lake Superior ore than had previously been necessary, and yet they produced a better pig iron at a lower cost. To complete the game, they sold, through brokers, their own inferior puddle cinder with high phosphorus content to these same competitors for $1 and $1.50 a ton.[39] The secret was in knowing how to flux the ore that was used. "What fools we had been!" said Carnegie. "But then there was this consolation," he continued, "We were not as great fools as our competitors."

Very early in its history the petroleum industry likewise sought the services of the scientist. Before Colonel Drake drilled his well near Titusville, Pa., in 1859, samples of petroleum had been sent to Professor Silliman, the younger, at Yale for his examination. He distilled the oil, separated the various fractions according to their boiling points, and reported that portions of these distillates were suitable for illuminating purposes. Men in the oil business, knowing that if a substitute for the expensive animal and vegetable oils that were then being used in lamps could be found it would have a ready market, acted upon Professor Silliman's advice and began the refining of petroleum in this country.[40]

In spite of this instance of the practical application of chemistry, it did not play much of a part in the methods of refining that were then used. They were crude and wasteful, utilizing only a little over 5 percent of the total mass of the crude oil. Not until 1870, when M. L. Hull of Cleveland devised the "vapor stove," were the naphtha fractions utilized; and then millions of gallons of naphtha, for want of a demand, were allowed to flow into the creeks and rivers, there to evaporate. Little change took place in the industry until 1885 or 1886, when a new source of petroleum was found in northwestern Ohio near the town of Lima. When the customary refining methods of distillation and treatment with sulfuric acid and alkali were applied to this Lima oil, they were found to be inadequate. Illuminating oils of suitable quality were not secured because the crude oil contained from ½ to 1 percent of sulfur. The industry was forced to turn to the chemist for a solution, but because of a long-existing prejudice against the "chemical fraternity," there was scarcely one trained petroleum chemist in the United States in 1885.[41] Out of this situation, however, came a much better understanding. Both the industry and the chemist came to realize that if practical solutions for refining problems were to be found, industry must be patient until the chemist had learned something about the refining industry. Since 1890, and particularly since the introduction of the internal combustion engine, research has played an increasingly important part in the petroleum industry.

Although some of the concerns to which the meat packers sold their by-products in a crude state had employed chemists, and the packers themselves had occasionally consulted commercial chemists, it was not until 1886 that a chemist (H. B. Schmidt) came to be regularly employed by a meat packer in the Union Stock Yards in Chicago.[42] Other packers soon followed suit in an effort to improve their products and to find use for various byproducts. "There was so much for the chemist to do in the packing industry in those days that it was simply a question of what pleased him best to work on." [43]

In the copper industry previous to 1884 the use of chemistry had been confined almost wholly to a few routine analyses by commercial chemists. In one instance Calumet and Hecla had employed an expert chemist to help them out of a chemical difficulty. "About 1884, a few chemists were employed in the earlier work of developing deposits in Montana and Arizona," but not until 1890 was the real value of

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[37] The inside history of the Carnegie Steel Company. See footnote 36.

[38] Carnegie, Andrew. Autobiography. Boston, New York, Houghton Mifflin Co., 1920, p. 182.

[39] The inside history of the Carnegie Steel Company, p. 64. See footnote 36: Autobiography, p. 183. See footnote 38.

[40] Burton, William M. Chemistry in the petroleum industry. *Industrial and Engineering Chemistry, 10,* 484 (June 1918).

[41] Chemistry in the petroleum industry, pp. 484–485. See footnote 40.

[42] Lowenstein, Arthur. Contributions of the chemist to the packing house products industry. *Industrial and Engineering Chemistry,* 7, 943 (November 1915).

[43] Contributions of the chemist to the packing house products industry. See footnote 42.

chemists in concentrating, roasting, smelting, and refining copper appreciated.[44] Since then their research and their improvements in analytical methods have made it possible greatly to improve the purity of the metal so vital to the electrical industry.[45]

A slowly increasing number of chemists found a demand for their services in such industries as pulp and paper, glass, chemicals, corn products, soap, photographic supplies, fertilizer. Some of the more venturesome individuals established commercial laboratories to which industrialists could bring their chemical problems. Most of these early laboratories have disappeared; but a few have survived, and many more have been founded.[46]

Although it must again be said that today much of the work done by these chemists would not be called industrial research, their efforts, nevertheless, resulted in better products at lower prices, new products from former waste materials, and other accomplishments which impressed the more foresighted industrial leaders with the importance of the new knowledge that was available to them, or could be made available if the chemist were given time and opportunity to become familiar with the requirements of industry.

The Creation of New Industries by Independent Investigators

The results achieved by many independent investigators, whose searches frequently gave rise to new industries, also attracted the attention of industrialists to the value of research. When John Winthrop, Jr., set up in Boston his curious chemical plant—"part druggist's shop, metallurgist's workroom, chemist's laboratory, and alchemist's den"—and made experimental batches of alum and saltpeter in an effort to provide the colonists with chemicals, medicines, and gunpowder, and to exploit the mineral resources of New England, he was but the forerunner of thousands of individuals in this country who have sought to apply their knowledge and skill in new ways. The records of the Patent Office bear witness to the uselessness, impracticality, and absurdity of many such efforts, but they also bear witness to accomplishments which have completely altered the way in which human beings live and the problems which they face. The names of Eli Whitney, Oliver Evans, Robert Fulton, Elias Howe, Samuel F. B. Morse, Obed Hussey and Cyrus McCormick, William Kelley, Alexander Graham Bell, and Charles Goodyear, immediately come to mind. For many years such individuals as these were pointing out the ways of technical progress. Most of them, although without the formal training that we now consider indispensable for the scientist and the engineer, were, nevertheless, possessed of "an intuitive insight which was unique, and an insatiable curiosity and a dogged determination to overcome all obstacles." Athough scores of men made important contributions to our technical and industrial development, the work of only a few of those whose accomplishments hastened the transition from isolated, unorganized research to cooperative, organized research in industrial laboratories can be mentioned here in any detail.

Hyatt and Celluloid

John Wesley Hyatt, a journeyman printer, working in Albany, one day read of an offer of $10,000, made by Phelan & Collander of New York, for a substance that could be used as a substitute for ivory in billiard balls. Undaunted by his scant knowledge of chemistry, he began to experiment nights and Sundays in the hope of gaining the reward. His efforts produced a number of useful plastic compositions, but none of them was suitable for billiard balls. One day his eye fell upon a bit of dried collodion about the size and thickness of his thumbnail, and as a result he began experimenting with nitrocellulose. Eventually, by making a solid core of another plastic material and covering it with nitrocellulose dissolved in ether and alcohol, he made a billiard ball. Many difficulties, however, stood in the way of a perfect product. A lighted cigar applied to the ball at once resulted in a serious flame and occasionally "the violent contact of the balls would produce a mild explosion like a percussion guncap," a feature that led one billiard saloon proprietor in Colorado, writing to Hyatt about his billiard balls, to say that he did not mind very much personally but that it was a bit dangerous, for every man in his saloon immediately pulled a gun.[47]

Hyatt's experiments with nitrocellulose continued, and he also designed special machinery for its manufacture and manipulation. In the winter of 1872–73 the Celluloid Manufacturing Company, in Newark, N. J., began to manufacture the first of the modern plastics. After 3 years Hyatt's financial backers finally allowed him to hire Frank Vanderpoel, a trained chemist, to systematize the process and perfect a quick and accurate method of determining the spent acids.[48]

Edison and the Electric Light

From a baggage-car laboratory fitted up with retorts and bottles discarded from railroad shops, Thomas A. Edison's curiosity, persistence, and skill were to carry

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[44] Herreshoff, J. B. F. Contributions of the chemist to the copper industry. *Industrial and Engineering Chemistry*, 7, 274 (April 1915).

[45] Contributions of the chemist to the copper industry, p. 275. See footnote 44.

[46] This volume, pp. 72–75.

[47] Hyatt, John W. Address of acceptance. *Industrial and Engineering Chemistry*, 6, 159 (February 1914).

[48] Address of acceptance. See footnote 47.

him to extraordinary success in business and to the realization of a boyhood dream—the possession of a well-equipped laboratory in which he could work day and night if he chose. The funds which he received from the sale of his stock-ticker made it possible for him to set up a workshop on the top floor of a padlock factory in Newark, N. J. In 1876, however, the desire for greater privacy and more room caused him to build a laboratory at Menlo Park. It was a "two story clapboard structure, long and unpretentious but exactly what he wanted."[49] Next to the laboratory in importance was the brick machine shop where skilled workmen constructed the innumerable pieces of equipment that Edison needed in his experiments. A small wooden carpenter shop, a gasoline plant that supplied the gasoline gas used for illumination, and a small building in which lampblack, made from a battery of smoking kerosene lamps, was collected and pressed into small cakes for use in the Edison carbon transmitter completed the facilities at Menlo Park.[50]

A private laboratory in which a man strove to make inventing a profitable business was a new thing and did not go uncriticized by the "pure" scientists of the day. Moreover Edison was looked upon as an unschooled intruder. His methods of research were not the traditional ones. He frequently disregarded the long-established rules deemed to be fundamental and relied on common sense and patient effort to carry him through a difficult problem. His motto was "Seeing is believing," and he would not give up the search for what he wished to see until he had exhausted every possibility. Over and over again he experimented with "a scrupulous integrity and a minute attention to detail" on problems the scope of which would have challenged even the best trained scientist. Each experiment was recorded methodically in notebooks, one of the most frequent entries being "T. A." meaning "Try Again."[51]

Edison has often been criticized for his "trial-and-error" method. But Dr. Karl T. Compton, who worked

FIGURE 6.—Interior View of Edison's Laboratory at Menlo Park, 1880

World Wide Photos, Inc

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[49] Jehl, Francis. Menlo Park reminiscences. Dearborn, Mich., Edison Institute, 1936, vol. 1, p. 7.

[50] Dyer, F. L., Martin, T. C., and Meadowcroft, W. H. Edison: his life and inventions. New York, London, Harper and Bro., 1929, vol. 1, p. 272.

[51] Menlo Park reminiscences, p. 338. See footnote 49.

in Edison's laboratory for a period during the World War, has said that although the method of continual search and trial underlay much of Edison's work, however, it is a mistake to think that all Edison's work was carried on by this search and trial method. Back of everything which he did or tried there was always an idea. The starting point was always the need of accomplishing some purpose, the second stage seemed to be the suggestion of various ways of accomplishing that purpose, and the final stage consisted in trying out these suggested solutions in as thorough and systematic a manner as possible in order to find the best.[52] Such a procedure can be found in any industrial research laboratory today.

Previous to the move to Menlo Park most of Edison's inventions were made in the field of telegraphy, but the 5 years of feverish activity after the move were to produce the phonograph, the carbon telephone, the chalk telephone, and the incandescent light.

A description of the steps involved in each of the hundreds of experiments during the long search for a suitable incandescent lamp may give some idea of the care and patience demanded of Edison and his helpers:

> First the raw material for the filament had to be chosen. . . . The second step was the preparation of the raw filament. This work Edison always did himself. Third, each filament had to be carbonized, a process he attended to personally on the experimental lamps. . . . Fourth, Kruesi supplied the copper wires, on the end of which short pieces of platinum had been twisted. Fifth, Boehm blew the glass stem, inserting in it the copper-platinum wires. Sixth, after being carbonized the filament was placed on the glass stem of the bulb. This delicate task (which sometimes took two or three days) was always performed by "Batch" in Edison's presence. Seventh, Boehm inclosed the stem with its filament within the fragile shell of a glass bulb. Eighth, I placed the bulb on the vacuum pump and began evacuating the air. . . . Ninth, after the vacuum was obtained, it was always Edison who drove out the occluded gases and manipulated the lamp. . . . Tenth, when the lamp was finished, it was given a life test. . . . (Lastly) after the lamp, good or bad, had finished its test he breaks it open and takes it to the microscope to study the filaments, seeking the reason for the failure of the slender black thread-like substance.[53]

Such labors occupied the days and nights until New Year's eve, 1879, when the public witnessed the demonstration of a new system of electric illumination. While scientists were accusing him of "the most airy ignorance of the fundamental principles of both electricity and dynamics" and demonstrating the impossibilities of any general system of illumination based upon the incandescent lamp, Edison solved the problem by painstaking research. Before many industries had even given thought to research, Edison was keeping 75 men busy conducting experiments, designing and building new electrical apparatus for them, and devising methods of measurements so that he could make the use of electricity practical. Sir James Jeans in his presidential address before the British Association for the Advancement of Science tried to give some idea of what such efforts meant to industry when he said, "Let us also remember that the economic value of the work of one scientist alone, Edison, has been estimated at three thousand million pounds."[54]

By 1881 Edison was living in New York because of his new business interests. Activities at Menlo Park soon ceased as one by one the men in the laboratory left to assume new responsibilities in the rapidly growing electrical industry. A new laboratory was established at Goerck Street and a dozen men, "mostly college graduates working for glory and not pay," were kept busy there testing and improving Edison's new dynamos.

While at Menlo Park Edison had devoted himself to his experiments and had given little thought to the problems of manufacturing the products which his experiments had made practical. In 1886, however, he built a much larger laboratory at Llewellyn Park and determined to develop there a "large industry to which a thoroughly practical laboratory would be a central feature, and ever a source of suggestion and inspiration."[55]

Another intensely active period in Edison's life followed the opening of the new laboratory. He gave his attention particularly to the development of his phonograph, motion picture camera, storage battery, and dictating machine, while a rapidly expanding manufacturing plant turned out the products perfected in the laboratory. In 1917 he left his interests in the hands of others and served the government for 2 years on problems created by the war. But in 1919 he was again back in his laboratory where in 1929, 2 years before his death, he was still working 16 to 18 hours a day.

The laboratory at West Orange now has a staff of 107 persons and continues to serve as the center of research and development for the various interests of Thomas A. Edison, Inc.

Acheson and Carborundum

In the fall of 1880, a young man, jobless but with a keen interest in electricity, arrived at Edison's laboratory at Menlo Park. A white lie got him on the pay roll. After a short time in the drafting room, E. G. Acheson was placed in the original experimental department at $7.50 a week. Soon he was in the lamp factory learning all the details in preparation for arranging the exhibit of Edison's electrical inventions at the International Exposition in Paris. After the Exposi-

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[52] Compton, K. T. Edison's laboratory in war time. *Science, 75,* 71 (January 15 1932).

[53] Menlo Park reminiscences, pp. 344–346. See footnote 49.

[54] Jeans, Sir James. Presidential address. British Association for the Advancement of Science, *Report,* 1934, p. 18.

[55] Edison: his life and inventions, vol. 2, p. 369. See footnote 50.

tion he assisted in constructing machine shops and lamp factories to operate the Edison patents in Europe, and it was 1884 when he returned to New York only to leave Edison and try some experimental work on a scheme for "controlling electric currents, regulating dynamos, etc." Finding two backers, he built a "new style of dynamo" which proved to be a failure, for, although it would produce a current of immense amperage, the voltage was absurdly low. "Another failure added to a long list," he said. His next experiment, on an anti-induction telephone wire, was made by taking "a rubber-covered wire, coating it with graphite, passing it through a copper solution and plating on it a tube of copper; next braiding cotton over the tube; then soaking the cotton with asphaltum; then covering the whole with a lead pipe covering." He patented the process which a short time later he sold to Mr. George Westinghouse for $7,000 in cash and $50,000 in stock of the Standard Underground Cable Company, which, however, because of a reduction in the company's capital, was soon reduced to $16,666.

After a 3-year term as electrician to the Cable Company at a regular salary, Acheson conceived the idea that if he could establish a small electric lighting plant in some town, he could make the plant pay its way by night-lighting and yet use the dynamo for experiments during the day. Monongahela City was selected as the location. He soon turned his attention to making rubber synthetically and succeeded, in 1891, in producing a small piece. Unfortunately, one of his partners in the lighting enterprise arrived in Monongahela City to see the plant just after investing considerable money in a rubber tree grove in Mexico, where he intended to produce more rubber than the world would use, and advised Acheson to shut the plant up and "throw it into the Monongahela River." Acheson lost interest in rubber, not even making a record of how he produced his sample; but ignoring the advice, he turned his plant to new uses.

The value of an artificial abrasive had been brought to his attention by a chance remark made in 1880 by Dr. George F. Kunz, of Tiffany & Company. He decided to try to produce one. The recollection of an experiment which he had once conducted for his brother on the reduction of iron from its ores by the use of natural gas suggested a starting point, for in this experiment some clay articles placed in a highly heated furnace into which natural gas was passed had, when cold, been found to be thoroughly impregnated with carbon. The procedure by which Acheson discovered the material to which he gave the name Carborundum is described in his own words:

> An iron bowl, such as plumbers use for holding their melted solder, was attached to one lead from a dynamo and filled with a mixture of clay and powdered coke, the end of an arc light carbon attached to the other lead was inserted into the mixture. The percentage of coke was high enough to carry a current, and a good strong one was passed through the mixture between the lamp carbon and bowl until the clay in the center was melted and heated to a very high temperature. When cold, the mass was examined. It did not fill my expectations, but I by sheer chance, happened to notice a few bright specks on the end of the arc carbon that had been in the mixture.[56]

One of these specks, when mounted on the end of a lead pencil and drawn across a pane of glass, cut it like a diamond. After patient work with a small furnace made of bricks, Acheson had enough of his material to take to the lapidaries in New York City. It was during the journey that the substance received its name, because of the discover's hunch that it was composed of carbon and corundum, a hunch that later proved to be a mistake, for carborundum is a compound of carbon and silicon. In New York a diamond cutter bought the tiny supply at 40 cents a carat or at the rate of about $750 a pound.

Upon his return from a trip to Europe, where he sold the foreign patent rights, Acheson heard of the new electrical development at Niagara Falls. After inspection of it, he placed before his directors a plan for building a new plant equipped for a thousand horsepower. To do this, in the face of the fact that the Monongahela plant, using only 134 horsepower, was producing twice as much as was being sold, entailed too great a risk for them, and they resigned. But Acheson went on with his plans, and although eventually forced to appeal to some Pittsburgh bankers for assistance, the Niagara Falls works were started in the fall of 1895. By 1910, although Mr. Acheson had lost control of it, the company was using 10,000 horsepower and producing carborundum at the rate of 10,000,000 pounds a year. A new industry had been created, the value of the product proved, and a market for it found even though the country had been passing through a financial depression. But Acheson's contributions to industry were not over. Under patents secured in 1895, 1896, 1899 he began the manufacture of graphite. Other experiments followed and in 1906, while trying to increase the value of carborundum as an abrasive, he found in the furnace a small amount of "a very soft, unctuous, noncoalescing graphite" which he immediately recognized as an ideal lubricating product. More experiments resulted in a method of suspending graphite in water to form a lubricant called Aquadag. The next step was the transference of the graphite from the water medium to an oil medium, to form an improved lubricant called Oildag. Acheson felt that those two products would probably prove to be of more value to the world than any of those he had previously developed.[57]

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[56] Acheson, E. G. A pathfinder: discovery, invention and industry. New York, The Press Scrap Book, 1910, pp. 98–99.

[57] A pathfinder: discovery, invention and industry, p. 129. See footnote 56.

Hall and Aluminum

Shortly before Acheson built his plant at Niagara Falls for the manufacture of carborundum, another industry resulting from the persistent research of an individual had located there. As a schoolboy, Charles M. Hall received his first knowledge of chemistry from a textbook that his father had studied in college during the 1840's. Aluminum was mentioned in this book, but Hall did not begin experimenting to find a process for making it cheaply until the fact had dawned upon him that although every clay bank was a mine of aluminum, the metal was as costly as silver. The first experiments were not undertaken very seriously because he was then a student in college and already working on "three or four other attempted inventions." An introduction to the subject of thermochemistry and a close association with his professor in chemistry, Frank Fanning Jewett, increased his knowledge and led him gradually to the idea that aluminum could be obtained by electrolysis. Beginning in 1886 to experiment on such a plan, he made many tries, until finally he "took some cryolite and found that it melted easily and in the molten condition dissolved alumina in large proportions." Putting some of this molten mass in a clay crucible, he passed an electric current through it from a small electric battery rigged mostly from parts borrowed from Professor Jewett. At the end of 2 hours he poured out the melted mass but found no aluminum. A repetition of the experiment with a carbon crucible enclosed in a clay crucible brought greater success, for in the bottom of the carbon crucible were a number of small globules of aluminum. Hall was convinced that he had found the process he was seeking, but it was not easy to convince others. Within 3 years two groups of backers became discouraged and gave up. A third group formed the Pittsburgh Reduction Company—now the Aluminum Company of America—and in the summer of 1888 began to build and operate a commercial plant in Pittsburgh which produced 50 pounds of metal a day, that sold for $2 a pound. Soon the company erected a larger plant at Niagara and, by 1911, had a third plant and was producing 40,000,000 pounds a year. The price had fallen to 22 cents a pound.

From 1888 until 1914, the experimental development of the company's various manufacturing processes was carried on in its plants and chemical laboratories under Hall's direction. After his death experimentation continued in the different plants under the direction of the superintendents, and in certain plants under the direction of the central engineering organization, but in 1917 it was decided to centralize this work in one organization reporting directly to the management. In January 1918 Francis C. Frary was hired to organize the research work of the company. The war delayed his plans, and it was not until he was released from military service in December 1918 that he really started to build up the research organization for the Aluminum Company of America.

Baekeland and Bakelite

In 1889, as part of his reward for winning a prize in chemistry, Dr. Leo H. Baekeland, professor of chemistry and physics in the Government Normal School at Bruges, Belgium, was able to make a trip to the United States. An enthusiasm for photography and an interest in the new photographic processes which were being developed had already brought him some reputation in this branch of the chemical industry. Once in New York, Baekeland was offered a position as chemist in the factory of E. and H. T. Anthony & Co., makers of photographic films and bromide paper. He accepted the position, resigned his post at the Government Normal School, and decided to remain in America.

After 2 years with this company, he left it to become a consulting research chemist and to try, as he expressed it, "to work out, without sufficient financial means, several half-baked inventions, the development of each of which would have required a small fortune."

During a long convalescence Baekeland reached the decision that he would focus all his attention upon the project which seemed most likely to bring him the quickest results. With the financial backing of Leonard Jacobi, he tackled the problem of manufacturing some new types of photographic paper. Although the technical difficulties were soon overcome, the business did not at once become a profitable one; it took 6 years to convince the picture-taking public that Velox was a good product. Once that was done, the Eastman Kodak Co. offered Baekeland cash for his interest in the enterprise, and he accepted it.

After an interlude of study and work during which he helped to perfect a process for manufacturing caustic soda and chlorine, Baekeland began the work which was to bring him fame—the study of the action of formaldehyde upon phenols. Other chemists had sought to fathom the mysteries of this reaction, but had obtained like Kleeberg a worthless, insoluble mass of material, or like Blumer and De Laire special resinous substances with practically all of the general properties of natural resins. Baekeland was not much interested in synthetic resins, which at that time cost more to produce than the natural products and were in some respects inferior to them, but he was fascinated by the hard mass for which Kleeberg had been unable to find a solvent. After many attempts, Baekeland, too, had to give up as hopeless the search for a solvent.

Making a fresh start, he studied exhaustively each step in the complicated chemical reaction and eventually learned how to control it at whatever phase he desired. Then followed the discovery of a practical method for producing a substance that would remain fusible and plastic while it was being formed or molded, and yet could under the action of heat be polymerized and hardened to the state where it was no longer fusible or soluble.

Baekeland still had to convince himself that the new substance could be produced upon a commercial scale and that it could be used satisfactorily for industrial purposes. Consequently, he installed a working unit in which under various conditions the material could be prepared in ton lots. From the early experiences of those who used the material Baekeland learned much. Because the methods of handling bakelite differed so radically from those involved in the manipulation of rubber and celluloid, Baekeland encountered great difficulty in teaching some of his prospective customers how to work the new material. Consequently he abandoned his idea of allowing the use of his patents on a royalty plan and concluded that the best way was "to conduct the manufacture of the raw materials to beyond the stage where chemical knowledge or too much experience is required." Once this decision was made, Baekeland proceeded to organize factories in both this country and in Europe.

The Bakelite Corporation, now a unit of Union Carbide and Carbon Corporation, has had from the time of its founding a research laboratory and an experimental department for the carrying on of both fundamental and applied research.

Today the research and development laboratories are operated at Bloomfield, N. J. There, under the direction of Dr. George O. Curme, Jr., and Mr. Archie J. Weith, the correlation of the numerous types of plastics and their properties is being studied and new resins are being evaluated in terms of present-day industrial requirements. Fundamental research on synthetic organic resins for various uses is being carried on, and a great many experiments are under way in the development of compositions for use as molding plastics, impregnating materials, adhesives and bonding agents for plywoods, abrasives, resistors, and carbon brushes.

Other research is being conducted in such diverse fields as synthetic resin bases for the paint and varnish industry, heat-hardening lacquers, cast resinoids, cements, wire coating compounds, calendering, and coating compounds. In cooperation with industrial firms, research studies are being made to improve fabricating techniques, to develop more efficient molding processes, and to design faster production machines.

Growth of Organized Research

Period Preceding First World War

The preceding account of the efforts of men who were seeking to apply science to industry, either within the industrial organization itself or in their private laboratories, is far from being a complete one, but it is sufficient to show that after 1875 the application of science to industry was becoming increasingly effective and was receiving growing recognition and support from industrial leaders.

Until the end of the nineteenth century, however, industrial research remained for the most part an unorganized effort by individuals. Their accomplishments were many and important; but individuals working independently could not, for very long, provide the technical and scientific knowledge essential to a rapidly developing industrial nation.

Here and there farsighted executives saw the need for organized, coordinated, systematic research by trained scientists working together under favorable conditions and, soon after the turn of the century, took measures to meet that need by establishing in their companies separate research departments or divisions.[58] On the whole, those industries born in the laboratory or directly dependent upon new knowledge for their growth organized their research activities earlier and more rapidly than the industries which had long been established. In fact in 1920 approximately two-thirds of all the research workers who were recorded in the first survey of the National Research Council were employed in the electrical, chemical, and rubber industries.[59]

Several endowed institutes of research and an increasing number of commercial laboratories provided industry with additional facilities for carrying on research conveniently and inexpensively.

In spite of this increased activity, however, the number of companies carrying on research in 1920 was relatively small. That year the National Research Council published its first *Directory of Industrial Research Laboratories*, which contained about 300 names. This is a small figure when compared with the number of companies for which research was a sound undertaking.

Although after 1900 the technical journals and the proceedings of engineering societies published an increasing number of papers pertaining to industrial research, public interest was still small. Before the First World War popular and semipopular magazines

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[58] Since the story of organized research in this country can best be told not in generalities but in terms of specific experiences, one part of this paper sketches the growth of research in approximately 50 industrial laboratories. See pp. 42–75.

[59] Perazich, G., and Field, P. M. Industrial research and changing technology. Philadelphia, Pa., Work Projects Administration, National Research Project, *Report No. M-4*, 1940, pp. 41–42.

contained little mention of industrial research. In the *Readers' Guide to Periodical Literature* the distinction between scientific research and industrial research was not made until the publication of a *Supplement* covering the years 1907–15. In that volume six articles were listed under the heading "Industrial Research," but all of them discussed the subject in relation to England and were published in the English periodical *Nature*.

Long before the war, however, leaders of research in the United States were aware of Germany's accomplishments and pointed them out to American industrialists and educators in an effort to arouse interest and create conditions which would make for comparable achievements in this country. In 1911, Willis R. Whitney wrote:

> For the past 50 years that country (Germany) has been advancing industrially beyond other countries, . . . by new technical discoveries. In fact this advance may be said to be largely traceable to their apparent over-production of research men by well fitted universities and technical schools.[60]

He went on to point out that each year a few hundred new doctors of science and philosophy were graduated. Most of them had been well trained to think and experiment; to work hard, and to expect little. They went first into the chemical industry until it could absorb no more of them, and then into every other industry in Germany. They became the teachers, the assistants, and the professors of all the schools of the country. They worked for $300 to $500 a year, satisfied as long as they could make experiments and study the laws of nature. The intense and widespread activity of so many highly trained men soon manifested itself in many physical and electrical devices, and in hundreds and even thousands of new commercial organic products. "England and America had the raw material for such development. But Germany had the *prepared men* and made the start."

Effect of the First World War

The outbreak of the First World War immediately focused attention upon the technical and scientific developments that had given Germany such industrial strength and military power within a comparatively short time. Industrial research began to have significance for the general public. As F. B. Jewett expressed it:

> Newspapers, magazines and periodicals are continually publishing articles on it; vast numbers of people are talking, more or less knowingly, about it; and industries and governmental departments, which, up to a few years ago had hardly heard of industrial research, are embarking or endeavoring to embark upon the most elaborate research projects.[61]

The American Federation of Labor adopted resolutions urging the President of the United States and the leaders of Congress to foster in every way a broad program of scientific and technical research because it forms a fundamental basis upon which the development of America's industries must rest, because it greatly increases the productivity of industry, advances the health and well-being of the whole population, and raises the worker's standard of living.

American industry was threatened with a serious shortage when it could no longer get chemicals, dyes, medicines, and glass from Germany, but a united effort upon the part of scientists, industrialists, and Government officials soon relieved the situation. With America's entrance into the war, technical problems multiplied and the efforts of research workers increased in all the laboratories of the country. By the time of the armistice, practically every scientist possessed of any capacities for research had been called upon to aid the country with his special knowledge.

When the war began only Germany could supply the world with large quantities of diphenylamine—an ingredient necessary in smokeless powder to prevent its deterioration—and aniline, the raw material used in the manufacture of diphenylamine; the du Pont research laboratories, however, set to work at once to meet the demand for these materials and in 1918 diphenylamine was being manufactured at the rate of 1,000 pounds a day.[62]

A threatened shortage in the supply of sheet lead and an actual shortage in lead burners seemed about to prevent a tremendous expansion in the sulfuric acid industry that the increased call for explosives was making necessary. Again the research laboratory solved the problem, and in 1918 millions of pounds of sulfuric acid were being manufactured in plants that did not have a pound of lead in their construction.[63]

Another serious shortage was averted because shortly before the war the research laboratory of the du Pont Company had discovered the presence of potash salts in its nitrate deposits in Chile and had found a satisfactory method for their extraction. The company was in a position therefore, to undertake the immediate production of them on a commercial scale.

Other industrial research laboratories were equally active. The Eastman Kodak Company became the main source of many chemicals essential to photography and to the work in laboratories of universities and industry. It also made extensive studies during the war in aerial photography and naval camouflage. In the General Electric laboratories a small but powerful X-ray generating outfit was developed by W. D. Cool-

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[60] Whitney, W. R. Research as a financial asset. *Scientific American Supplement, 71*, 347 (June 3, 1911).

[61] Jewett, F. B. Industrial research. (*Reprint and Circular Series of the National Research Council*, No. 4.) Washington, D. C., National Research Council, 1918, pp. 2–3.

[62] Reese, Charles L. Developments in industrial research. *American Society for Testing Materials, Proceedings, 18*, pt. 2, 37 (1918).

[63] Developments in industrial research, p. 37. See footnote 62.

idge with the aid of C. F. Kettering and the Victor X-Ray Company. Two months before America entered the war, the Submarine Signal Company of Boston, and the General Electric Company, aided a little later by the Western Electric Company, had taken the first steps toward developing a submarine detector. By November 1917, the famous "C" and "K" tubes were ready for trial installations, and their performance proved to be superior to any other detecting device that the country produced before the armistice was signed. An appreciable percentage of the personnel of the Westinghouse Laboratories went into various departments of the Government during the war. In many other research laboratories, facilities, money, and men were placed at the service of the country in meeting the problems caused by the war in Europe and later by our participation in it.

American chemists and chemical manufacturers were harshly criticized during the war for having failed to develop an American dye industry. They replied with various explanations. "The United States," said Bernhard C. Hesse, "had persistently and deliberately declined to bring about economic conditions which those who were in a position to know told them were essential to the establishment of an independent coal-tar color industry in this country." [64] A. D. Little gave a different explanation of the lack of dye industry when he said:

> The plain underlying reason why we have been unable during thirty years of tariff protection to develop in this country an independent and self-contained coal-tar color industry while during the same period the Germans have magnificently succeeded is to be found in the failure of our manufacturers and capitalists to realize the creative power and earning capacity of industrial research.[65]

Whether either of these statements gives a completely satisfactory explanation of America's dependence in 1914 upon Germany for dyes and dye intermediates is doubtful and beside the point here. The significant fact for this survey is that in cooperation with the Government, American industrialists established a dye industry which American scientists have continued to advance technically. The foundation of the industry was laid when A. M. Palmer, alien property custodian, and Francis P. Garvan, his colleague, became convinced that the German patents would not only provide a solution of the immediate problem, but would also serve to protect the new industry against German competition after the war.[66]

When the Trading with the Enemy Act was first drawn up it did not provide the alien property custodian with authority to take over enemy owned patents, but an amendment to the act remedied this defect. The idea was then conceived of putting the patents in the hands of an American institution strong enough to protect them. An effective barrier to German importations after the war would thereby be erected and American industry would be freed from the prohibition enforced by the patents against manufacture. The Chemical Foundation, Inc., originated by Garvan and approved by President Wilson, came into existence and acquired about 4,500 of the former German chemical patents. It was not to operate any patent itself, but merely to issue nonexclusive licenses for the patents for a small fee to persons, firms, or corporations wishing to participate in a competitive chemical industry. After certain provisions for the retirement of preferred stock were met, all surplus income went to the support of research.

Although Garvan had had no formal scientific training, he believed wholeheartedly in the importance of applied science, and, as rapidly as funds were available, he used them to support chemical research and to educate the public in the importance of the chemical industries. The paper research laboratory at Savannah, Ga., which, under the direction of Charles H. Herty, has developed processes for the utilization of southern pine in the manufacture of newsprint paper is an outstanding example of research made possible by the fund of the Chemical Foundation. In 1934 Garvan organized the Farm Chemurgic Council in an attempt to bring together the leaders of science, agriculture, and industry for an attack upon the problems that have faced agriculture for many years.

In 1916, when the National Academy of Sciences offered its services to the Government, President Wilson asked it to organize an advisory committee and various subcommittees to coordinate and make available to the Government the research resources of nongovernmental institutions. The National Research Council was formed as an operating agency of the National Academy of Sciences, and its work was so effective that in May 1918, again at the request of President Wilson, it was given permanent organization.[67]

Early in the war the submarine problem and the development of antisubmarine devices engaged the attention of the Council. Fifty engineers and physicists, called together to determine what had already been done in this field, formed special groups to deal with various phases of the problem. Scientists from the Allied countries came to America to report what

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[64] Hesse, Bernhard C. Contribution of the chemist to the industrial development of the United States—a record of achievement. *Industrial and Engineering Chemistry*, 7, 297 (April 1915).

[65] Little, A. D. The dyestuff situation and its lesson. *Industrial and Engineering Chemistry*, 7, 239 (March 1915).

[66] The Chemical Foundation. *Scientific American*, 120, 315 (March 29, 1919).

[67] Barrows, Albert L. The relationship of the National Research Council to industrial research. This volume, pp. 365–370.

research was being carried on in their countries, and, in order to prevent duplication of effort, scientists were attached to the American embassies in London, Paris, and Rome to keep in close touch with research activities among the Allies. The Council's Divisions of Physics, Mathematics, Astronomy, and Geophysics dealt with 70 major problems in connection with range-finding and the pressures and velocities involved in the discharge of large guns. The Chemistry and Chemical Technology Division had 40 problems assigned to it. A thoroughgoing study of primers was made; a special committee was formed to deal with the problem of fixation of atmospheric nitrogen; and other groups worked upon charcoal for gas masks, fuel for motors, the toxicology of gases, and difficult problems in ceramics and refractories. The Engineering Division of the Council had 14 committees at work and maintained close cooperation with the engineering societies. The Division of Agriculture was active on problems of production and conservation while other groups of scientists carried on investigations in meteorology, geology, road building, medicine, and psychology.[68]

Such organized effort resulted within a short time not only in the solution of numerous wartime problems, but also in the discovery of many facts that were to provide the basis for great peacetime industries. The effectiveness of cooperation in research was clearly demonstrated, but the concentration of all the research resources of the country upon the immediate problems of a warring nation had at least one serious drawback, which Dr. Jewett pointed out at a meeting of the Royal Canadian Institute shortly after the war. He said:

> The results of the research activities throughout the war have been simply astounding, even to men whose whole training and experience have been along this line. Few, however, realize the exact price paid for these results or appreciate fully the reactions on the orderly peace-time life of the nations brought about by the diversion of our educational and research energies toward the one common purpose of human destruction. With the picture of recent scientific war-time achievements before us, it is difficult to realize that in setting up the machinery to accomplish these achievements we at the same time set up the machinery for the destruction of advances beyond a certain point. By robbing the colleges, universities, and industries of their trained scientists and employing them in war's scientific sweat-shop, it was inevitable that stupendous results should be obtained. By so doing, however, we cut off completely the possibility of further advances into the realm of the unknown and likewise destroyed our chance of developing new men to carry on the investigational work of the old, when the latter were worn out. . . .
>
> While I am not in a position to know the exact situation elsewhere in the world, I do know that we in the United States had early in the summer of 1918 arrived at the state where scientific man-producing machinery no longer existed.[69]

In contrast to this point of view, however, was that of Dean W. R. Thatcher, of the University of Minnesota, who felt that the increased appreciation of the practical value of research and the enhanced respect for the research worker, resulting from America's experience during the war more than counterbalanced the temporary concentration upon wartime problems.[70]

Organized Research a Major Industry

Since the First World War, industrial research has assumed the proportions of a major industry. Laboratories organized before the war have expanded their facilities and increased their staffs; new laboratories have been established by companies seeking to maintain or improve their position in the industrial order by using more efficient methods, by making better products, by developing new products, and by being equipped to meet the changes that come through science and technology. In 1920 about 300 laboratories were engaged in industrial research; in 1940 the number had increased to more than 2,200. Meanwhile the total personnel had grown from approximately 9,300 to over 70,000.[71] The 2 periods of most rapid expansion were from 1920 to 1931 and from 1933 to 1940. Between 1931 and 1933, the business depression caused many companies to curtail their research activities and to reduce the number of workers in their laboratories. In 1930, when the National Research Council revised its *List of Industrial Research Laboratories*, 1,625 industrial establishments reported a total research personnel of 34,212. A second report in 1933 showed 1,455 laboratorics reporting a total personnel of 22,312, a decrease of almost 35 percent. Nearly 44 percent of the laboratories, however, kept their personnel intact, and about 13 percent increased their staffs. The greatest decline in the employment of research workers occurred in the larger laboratories, of which only 22, employing more than 100 men each in 1930, accounted for a total decrease of 3,119.[72] By 1935, however, the lost ground had been recovered in most industries, and for the last 5 years the total personnel in research laboratories has showed a marked gain.

In their study of "Industrial Research and Changing Technology" George Perazich and Philip M. Field have pointed out some significant features about the postwar growth of research.

> In the interval between 1927 and 1931 laboratory personnel grew by approximately 14,000 workers, more than half of whom were employed by the electrical, petroleum, and industrial-chemical industries. In the seven years following 1931, laboratory personnel of all companies grew by 11,500 more workers.

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[68] Howe, H. E. The stimulation of research. *Scientific American, 120,* 518–519 (May 17, 1919).

[69] Industrial research, pp. 3–4. See footnote 61.

[70] Angell, James Rowland. The development of research in the United States. (*Reprint and Circular Series of the National Research Council,* No. 6.) Washington, D. C., National Research Council, 1919, p. 17.

[71] Cooper, Franklin S. Location and extent of industrial research activity in the United States. This volume, pp. 174 ff.

[72] West, C. J., and Hull, Callie. Survey of personnel changes in industrial research laboratories—1930–1933. *Research Laboratory Record, 2,* 154–58 (September 1933).

About half of this growth was due to the increase in staffs of producers, of agricultural implements, industrial chemicals, petroleum, and rubber.[73]

The same source shows that there has been an impressive increase in the number of large laboratories. Fifteen companies in 1921 maintained research staffs of more than 50 persons; by 1938 there were 120 such companies. Their growth was—

> . . . eightfold (as) compared with about a threefold rise for companies with fewer than 11 persons on their research staffs. . . . Thirteen companies with the largest research staffs, representing less than 1 percent of all companies reporting in the National Research Council survey, employed in 1938 one-third of all research workers, or as many as the 1,583 companies with the smallest research staffs.[74]

During this period concentration of research workere in the laboratories of a few companies within an industry became more marked.

> . . . In rubber, for instance, a quarter of the reporting companies employed 90 percent of the research personnel in the industry; in petroleum and industrial chemicals the respective percentages were 85 and 88.[75]

In 1938 the largest number of research workers was employed in the chemical and allied industries.

> . . . Next in importance were petroleum; electrical communications; electrical machinery, apparatus, and supplies; other machinery industries; and rubber products . . . In that year more than half of all those working in industrial research laboratories in the United States were employed by the chemical, petroleum, and electrical industries (including communications, utilities, radio, and the manufacture of electrical machinery, apparatus, and supplies.)[76]

From 1927 to 1938 there was a gain in the number of research workers in the petroleum industry of 538.7 percent while during the same period the increase in the radio and phonograph industry was 1,600 percent.[77]

With the remarkable growth of industrial research since 1920 have come a better coordination of all research activities and a more cooperative approach to the problems common to companies within an industry. The National Research Council, in addition to promoting research, has fostered among the scientific organizations and institutions of the country a coordinated program of research in the interest of the general welfare. To assist more directly the research interests of industry, the Council has established the Division of Engineering and Industrial Research.[78] The greater part of the Council's membership is "composed of representatives of some 85 national scientific and technical societies." Nearly 1,000 persons are members of the many committees that have been formed to represent the major fields of science.

In addition to their work with the National Research Council, the engineering societies have expended much effort and money to promote important joint research projects. In 1926 the Special Research Committee of the American Engineering Council presented a 5-year program of research estimated to cost $335,000 that would benefit both industry and agriculture. In 1938 a Special Committee on Scientific Research Legislation presented a report, which was approved by the American Engineering Council, stressing the need for more coordinated and scientifically directed research as "essential to the maintenance of adequate national defense" and "investment in the public welfare." This report also urged careful study of the ways in which the Federal Government could aid and encourage research without interfering with the existing or prospective research of individuals, corporations, and educational institutions.

The Engineering Foundation, the research agency for the engineering societies in civil, mechanical, electrical, mining, and metallurgical engineering, is likewise active in coordinating research activities. In 1937 the laboratories of 14 universities and 2 Government bureaus were working with it in an effort to solve technological and human problems in the engineering fields. In addition the Engineering Foundation has sponsored long-term research projects in alloys of iron and in welding, the latter project embracing more than 60 fundamental studies in college and industrial laboratories and a compilation of welding literature.[79]

Many special and joint research committees in the various engineering societies are active in furthering coordinated and cooperative research projects. In one of the worst years of the depression, 1931, the American Society of Mechanical Engineers had 460 men, 50 percent of whom were not members of the society, voluntarily serving on 28 such committees. To finance the society's research activities of that year, $40,500 was contributed by industry and other interests outside the society. Some 25 technical societies, trade associations, and Government bureaus cooperated with the committees as joint sponsors and financial supporters of the various projects.[80]

A cooperative attack upon common problems by companies in the same industry is not a new procedure, but it is one that has become increasingly important in the last two decades. In the late eighties the cane-sugar producers in Louisiana were threatened by the

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[73] Industrial research and changing technology, p. 6. See footnote 59.

[74] Industrial research and changing technology, pp. 8–10. See footnote 59; Location and extent of industrial research activity in the United States. See footnote 71.

[75] Industrial research and changing technology, p. 10. See footnote 59.

[76] Industrial research and changing technology, p. 18. See footnote 59.

[77] Industrial research and changing technology, statistical table, p. 19. See footnote 59.

[78] The relationship of the National Research Council to industrial research, pp. 365–369. See footnote 67.

[79] Cooperative engineering research. *Industrial and Engineering Chemistry* (*News Ed.*), *15*, 83 (February 20, 1937).

[80] American Society of Mechanical Engineers. Reports and papers research committee. New York, The Society, 1932, p. 3.

competition of the beet-sugar producers. For years the latter had been working with the chemist and the agronomist to raise the sucrose content of the beet root and to find processes that would improve the yield of sugar and make molasses and all the other byproducts sources of profit rather than loss. The net cost of beet sugar fell year after year until it was sold at prices comparable to those of cane sugar. Faced with this grave competition the cane-sugar producers decided to meet it with the same methods that had created it. They called Dr. W. C. Stubbs to Louisiana, and under his direction, established the Sugar Experiment Station at Kenner. It was moved later to Audubon Park, on the outskirts of New Orleans.[81] From funds contributed entirely by the cane-sugar planters of Louisiana, a complete sugar house was erected upon a scale large enough to give commercial results. About $100,000 worth of equipment for the station was obtained either by purchase or gift.[82]

Stubbs soon found that there were many inefficient practices in the cane-sugar industry that could be remedied by proper scientific control. When the planters began, however, to look for chemists and engineers to provide this control, they were faced with another problem, for outside of Europe there were few men who knew much about the chemistry of sugar. Undaunted, the Louisiana Sugar Planters' Association met and decided to establish in connection with the Sugar Experiment Station a school for training the experts they needed. Under the direction of Stubbs, the Audubon Sugar School was opened in 1891. The whole enterprise was so successful that it was taken over by the State and became a part of the Louisiana State University.

Research is today an accepted and important part of the work carried on by many trade associations. Discussing in detail in another section of this report the research activities of these associations, Charles J. Brand states that of the 330 trade associations listed in the survey of the National Research Council 36 maintain their own research laboratories, and at least 54 others conduct technical research in some other way.

A cooperative attack upon problems other than technical ones is now being made by a few industries. Various means exist by which research directors and laboratory executives can exchange information and study jointly the common problems of organization and management. One group of executives representing 28 companies in widely different industries located in many different parts of the country has met at various times since its formation 2 years ago to discuss problems arising from the maintenance of research laboratories.[83]

Since the study of science and the technique of experiment became parts of the curriculum of educational institutions in this country, university laboratories have been the source of innumerable scientific contributions to industry.[84] The proper relationship between the university and industry in the matter of industrial research is, however, a difficult one to determine and perhaps an even more difficult one to maintain. Nevertheless, during the last 20 years means have been evolved by which the university and industry can cooperate to their mutual advantage. Through practice schools and cooperative courses both faculty and students become cognizant of the practical problems which are involved in the successful application of science to modern industry. As a result industry is supplied with men better qualified to enter its research laboratories and its development departments. Through engineering experiment stations and divisions of industrial cooperation, the knowledge of specialists and the unique facilities of university and technical school laboratories are made available to industry, without interfering with the educational program, and often in fact, with benefit to it.

A few years ago Dr. Vannevar Bush in writing about the educational institution and industrial research said:

> Where an institution has unique facilities, and outstanding staff of specialists, and a location in the midst of intense industrial development, it is certainly incumbent upon it to play a part in the industrial world about it, not only because its existence may thereby become a matter of greater utility to industry, but also because the resulting relationships when properly nurtured are capable of exerting a profound and beneficial influence upon its educational processes. This is especially true in a case of a school of engineering, where the relationship between the pedagogical processes and many types of industrial problems is particularly close; but it applies as well to an institution of science, where that science is applied, whatever may be the field.[85]

Some Economic and Social Aspects of Industrial Research

Science and the research laboratory played but a small part in furthering the early technical developments in industry. Lewis Mumford in his *Technics and Civilization* wrote:

> . . . The detailed history of the steam engine, the railroad, the textile mill, the iron ship, could be written without more than passing reference to the scientific work of the period. For

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[81] Coates, Charles E. An experiment in the education of chemical engineers. The twenty-fifth anniversary of the Audubon sugar school. *Industrial and Engineering Chemistry*, *9*, 379–380 (April 1917).

[82] An experiment in the education of chemical engineers. See footnote 81.

[83] Worthington, C. G. Coordination between industries in industrial research. This volume, pp. 85–87.

[84] Papers describing contributions of research laboratories in universities to industry, have been published but no comprehensive study of the subject has as yet been made.

[85] Bush, Vannevar. The educational institution and industrial research. *Research Laboratory Record*, *2*, 35 (November 1932).

> these devices were made possible largely by the method of empirical practice, by trial and selection: many lives were lost by the explosion of steamboilers before the safety-valve was generally adopted. And though all these inventions would have been the better for science, they came into existence, for the most part, without its direct aid. It was the practical men in the mines, the factories, the machine shops and the clockmakers' shops and the locksmiths' shops or the curious amateurs with a turn for manipulating materials and imagining new processes, who made them possible.[86]

Although the "practical men" and the "curious amateurs" continue to make their contributions to the technical progress of the country's industries, the importance of their work, compared with that done by trained scientists and engineers cooperating in organized laboratories, has, for the last 50 years, been steadily diminishing. In the universities and in industry, trained chemists, physicists, metallurgists, mathematicians, and biologists have been continually pushing outward the frontiers of science. The detailed history of the electric light, telephone, camera, aeroplane, radio, of paper, rubber, chemicals, alloys, and plastics could not be written without repeated reference to science and the industrial research laboratory. No longer can the knowledge upon which further important technical advances depend be supplied by the "clockmakers" and the "locksmiths." Even though more great inventors of the stature of Edison, Diesel, and Sperry appear, as they unquestionably will, "the results of extensive research will be the raw materials upon which their inventive work will be exercised." [87]

No comprehensive account of the economic and social importance of the industrial research laboratory can be written until the many developments that have emerged from it have each been studied in great detail. These developments are so numerous and often so far-reaching in their effects, as in the case of the incandescent light, the internal-combustion engine, or the radio, that a complete account will probably never be possible. Nevertheless some of the more obvious and immediate economic and social results of industrial research can be observed.

The application of science to industry has helped to remedy some of the less desirable consequences of technical change: Natural resources have been conserved and former waste materials have been turned into useful products through organized research. Simple analyses by a trained chemist made valuable the enormous piles of flue cinder and roll scale that had been discarded from the heating furnaces and mills in the iron industry. No longer do millions of gallons of naphtha, for want of a demand, flow into the creeks and rivers to evaporate. No longer do the meat packers bury in the swamps carloads of bones and heads or pollute the streams with blood and tankage from their slaughterhouses.

In 1907 nearly seven-eighths of the coke made in the United States was produced in beehive ovens, where only the fixed carbon of the bituminous coal was saved and all volatile constituents were wasted. That same year, however, 5,607,899 tons were produced in byproduct recovery ovens, and the value of the gas, tar, and ammonia obtained from them amounted to $7,548,071. At the prices which prevailed in 1907, the value of the byproducts wasted in beehive coke ovens has been estimated at a little over $55,000,000.[88]

The manufacture of the type of powder used by the United States Army in 1918 required great quantities of alcohol and ether which, because of their volatility, were largely lost during the powder manufacturing process. Industrial research made it possible to devise methods which, at the scale of operation in 1918, resulted in a saving of 50,000,000 pounds of these solvents each year. Similar changes in the process of making guncotton saved 45,000,000 pounds of nitric acid, an economy particularly important in the days when nitric acid had to be made almost entirely from Chile saltpeter.

A more recent example of the economic benefit resulting from industrial research is found in the petroleum industry, where in 1936 the cracking process made it possible for the refineries of the world to conserve 1,865,000,000 barrels of crude oil. Without this process it would have required 3,607,000,000 barrels instead of the 1,742,000,000 barrels of crude oil actually refined to have supplied the world's need for gasoline.[89]

New processes originated in the research laboratory have brought lower costs of production and improved products. James Gayley's invention of the dry-air plant eliminated the weather as a troublesome variable in the production of pig iron and brought a saving of from 50 cents to $1 in the cost of producing each ton, which for the year 1912 meant a saving of from $15,000,000 to $29,000,000.

Ten years ago it was estimated that the replacement of the carbon filament lamp by the more efficient tungsten filament, gas-filled lamp was saving the consumers of electric light in the United States about $2,256,000,000 a year.[90] Although probably inaccurate, this figure does give some hint of the magnitude of the savings which can come through industrial research. Wholly beyond calculation, however, are the social

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[86] Mumford, Lewis. Technics and civilization. New York, Harcourt, Brace and Co., 1934, pp. 215–216.

[87] Ferris, J. P. Research for industrial pioneering. *Mechanical Engineering, 54,* 249 (April 1932).

[88] Sadtler, S. P. Conservation and the chemical engineer. *American Institute of Chemical Engineers, Transactions, 2,* 109 (1909).

[89] Pioneers in research. *Oil and Gas Journal, 35,* u–21 (May 27, 1937).

[90] Carty, J. J. Science and progress in the industries. (*Reprint and Circular Series of the National Research Council,* No. 89.) Washington, D. C. National Research Council, July 1929, p. 3.

benefits which come with the relief of eyestrain and the prevention of nervous disorders.

Recently the research laboratory of a steel mill announced an electronic device that would substitute for the fallible human eye an electric eye for controlling the temperature in the process of making Bessemer steel. It is claimed that the accuracy made possible by this one result of a research project costing less than $75,000 will save the company $3 on every ton of steel it produces, or a potential yearly sum of $3,000,000.

Every automobile owner has shared directly in the results of the intensive research carried on by the manufacturers of tires. In 1908 a small tire cost $25; a large one $125. Each dollar bought about 50 miles of tire travel. In 1920 the estimated cost of tires for every 10,000 miles traveled was $163. By 1936 this figure has been reduced to $38.30. Dr. W. A. Gibbons, of the United States Rubber Company, has figured that if one assumes that this reduction in the price of tires since 1920 has not been a determining factor in bringing about the increased use of automobiles then the decrease in cost that has taken place has saved the public the enormous total of $35,083,000,000.

Impressive as are the new methods of industry, more impressive still are the new products which have been made possible through industrial research. In 1935 the American Chemical Society exhibited at the Exposition of Chemical Industries 75 industrial products that had been commercialized during the recovery period 1934–35. No product was exhibited whose origin could not be traced directly to an industrial research laboratory. Every person's life is influenced by direct contact with scores of new devices and products that did not exist 10 years ago, but far greater in number are the new materials used by industry, of which the layman knows little.

In 1911, W. R. Whitney wrote:

> Copper, iron, and five other metals were known and used at the time of Christ. In the first 1,800 or 1,900 years of our era, there were added to the list of metals in technical use (pure or alloyed) about eight more, or a rate below three a century. There has been so much industrial advance made within the past twenty or thirty years that fourteen new metals have been brought into commercial use within this period. This is almost as many in our quarter century as in the total preceding age of the world.[91]

Just a quarter of a century later C. M. A. Stine, speaking in 1936 at the annual dinner of the Wilmington Traffic Club, said:

> Lighter, stronger, rust-resisting metals were needed. The metallurgist and the electrochemist have developed more than 10,000 alloys that have gone into every department of industry. It was chiefly the demands of the automobile and the airplane that inspired this research, which in turn revolutionized steelmaking and all metal working . . .[92]

In any list of new products must be included multifarious chemicals, medicines, drugs, vaccines, and serums. If the byproducts of the wood, coal, and petroleum industries were also added, the total would be stupendous. By decreasing costs and improving quality, by relieving drudgery and suffering, and by increasing the opportunities for pleasure these new products have contributed to a higher standard of living.

The impact of new methods and new materials upon industry has brought, however, continual change; and change in a complicated industrial society inevitably means insecurity, temporary dislocation, and frequently disaster for many individuals. The rapidity with which this change sometimes occurs is well illustrated by the following description of events that took place as the tungsten lamp was being evolved.

> I have seen whole factories entirely overhauled a number of times in the past few years, in order to make the newest lamps. Not only have entire floors of complicated and expensive machines for making carbon lamps been thrown out and new machinery for making metal filament lamps installed, but before packing cases containing new machines could be opened and unpacked in the factory they have been thrown out as useless, as the advance from squirted metal filaments to drawn wire filaments proved the better way. Before the limit of factory efficiency on vacuum lamps could be reached, the introduction of nitrogen into the lamps brought the factories an entirely new factor, and now, before the consumers have more than commenced to feel the effects of the nitrogen-tungsten lamps, the manufacture of argon and its introduction into the incandescent lamp becomes a reality.[93]

Rarely can the shocks caused by technical changes be absorbed within a single company. The rapid development of the incandescent lamp, for example, eliminated any commercial possibilities for an ingenious lamp invented by Nernst and also greatly lessened the value of certain German patents covering a process for producing ductile tungsten. Hall's electrolytic process for producing aluminum at $1 a pound brought sudden idleness to Castner's plant which had been producing 500 pounds a day at a cost of $4 a pound. Likewise the development of mechanical refrigeration has made great inroads upon the market for natural ice. The successful production of synthetic indigo meant that the market for the crop from 1,000,000 acres of land in India had been destroyed. The discovery of an economical process for the fixation of nitrogen has freed the world from its dependence upon the nitrate beds of Chile, with the result that an important Chilean industry has sunk steadily into debt, and the country has lost a major source of revenue. Successful processes for the production of synthetic fibers and synthetic rubber have created new domestic industries and

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[91] Research as a financial asset, p. 346. See footnote 60.

[92] Stine, C. M. A. Change rules the rails. *Vital Speeches, 2*, 348 (March 9, 1936).

[93] Whitney, W. R. Relation of research to the progress of manufacturing industries. *General Electric Review, 18*, 872 (September 1915).

greater national self-sufficiency, at the expense, however, of the producers of natural fibers and natural rubber and at the risk of further disturbance to world trade.

Industrial research has added new factors to the competitive system in industry. To the struggle between companies in the same industry for the advantage that comes from lower costs of production and better quality of products has been added the rivalry for new knowledge. As one director of a research laboratory has expressed it:

> The keenest competition today is between revolutionary ideas. What the manufacturer of today fears is not so much the competitor who may shade production or selling ccsts a little, as the manufacturer who may virtually put him out of business by getting out something radically new that the customer prefers.[34]

Industries never before considered as possible rivals, have become competitors because of discoveries made in research laboratories. The petroleum industry, already a serious competitor of the coal industry, is rapidly becoming a producer of chemicals. The airplane, a product of intensive and highly complicated research, competes with the railroad train; the rubber industry, with the textile industry; and the chemical industry, with the cotton-growing industry.

Research has made more research imperative. Industrial strength can be achieved only through knowledge of what is taking place in the laboratory. In the face of constant change, industries maintain their stability only by being prepared for the next advance. For companies unable to support expensive research laboratories, the problem of keeping abreast of new developments is difficult; yet through trade associations, commercial laboratories, and universities the small concern has been able to strengthen its position through research. This necessity for seeking new methods and new products has brought new life to many companies. Inefficient methods have fallen before the impact of applied science; growth has replaced atrophy.

DEVELOPMENT OF ORGANIZED RESEARCH WITHIN INDIVIDUAL COMPANIES

For most of the material which follows, the author is greatly indebted to the executives and directors of research in the respective companies whose laboratories are described. In many instances the wording follows closely that of the accounts which were sent to him.

The reader will perhaps be aware that, in these pages many important laboratories are not discussed. The short time available for the preparation of this report made such omissions inevitable. By means of a questionnaire executives in every known research laboratory in the country were asked for historical material concerning the laboratories in their respective companies. An additional appeal was made to the directors of research in more than 75 laboratories known to be especially active in their industries. In some instances no reply was received; in others the account either was not historical in character or was too brief to be useful.

Chemicals

American Cyanamid Company

When the American Cyanamid Company acquired the American patent rights to the cyanamid process, there was a relatively small pilot plant in operation in Germany, an operating unit of commercial size in Italy, and a number of scattered plants under construction in Europe. To construct its first cyanamid unit at Niagara Falls, Canada, the company brought from abroad engineers, operating experts, and special items of equipment. An organization made up wholly of Americans was assembled, however, and in 1909 a research department was established to develop methods and means of converting the crude product into a fertilizer material which could be used in the American fertilizer mixtures. This research was carried on with the scattered facilities in the plant and in institutional laboratories.

In 1912 a formal research laboratory was established, and 3 years later a building was erected at Warners, N. J., to house its activities. At this time about six men spent their full time in the laboratory. With the outbreak of the First World War, the company, knowing it would be called upon for many products derived from cyanamid, organized a special staff to develop and produce them. Not until early in 1919 could this emergency service be abandoned and the personnel reorganized into a new research unit principally occupied with investigations of cyanamid derivatives.

During the 10 years from 1919 to 1929, the Cyanamid Company acquired three other enterprises: the Selden interests at Pittsburgh and Bridgeville, Pa., with a modern laboratory at Pittsburgh; the Calco Company at Bound Brook, N. J., with a highly developed laboratory; and the Lederle Laboratories, with an excellent central laboratory at Pearl River, N. Y., as well as some other widely scattered research facilities.

The laboratories at Warners and at Linden, having proved entirely inadequate, were abandoned; and a new research center was established at Stamford, Conn., which later absorbed the Pittsburgh and Bridgeville units. At present the company operates three major units: one at Stamford for research, both fundamental and applied, in pharmaceuticals and mining chemicals; one at Bound Brook for the study of coal-tar products; and one at Pearl River for the study of biologicals, serums, vaccines and for specialized pharmaceutical

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[34] Jewett, F. B. Address before the American Bar Association, July 1938. *Reports of the American Bar Association, 53*, 192 (1928).

work. Approximately 325 technical men, supplemented by 320 operating, clerical, library, and legal assistants, devote their entire time to research.

When facilities for the study of certain problems are unavailable in these three laboratories wholly under the control and direction of the company, other laboratories in institutions scattered throughout the country are used by means of a fellowship plan.

Dow Chemical Company

In 1887 Herbert Dow, a student at Case School of Applied Science in Cleveland, invented a new and economical process for extracting bromine from brine. Two years later he proceeded to put his electrolytic cell to work in a small flour-mill shed in Midland, Mich. Before very long his process was also adapted to the extraction of chlorine from brine, with caustic soda as a coproduct. These developments, at the end of 10 years, led to the consolidation of several parent companies to form the Dow Chemical Company.

A sister company, formed by Dow and his associates in 1901, and later purchased by the Dow Chemical Company, is conceded to have been the first one to carry on a synthetic organic chemical process on a commercial scale in America. The company manufactured sulfur chloride and reacted it with carbon bisulphide, producing carbon tetrachloride which, in turn, was treated with iron in the presence of water to produce chloroform.

The First World War shut off the European sources of chemicals and stimulated the company's production of aromatic organic compounds. The output of phenol was increased to 30 tons a day, and a new process was developed for the manufacture of synthetic brominated indigo.

The end of the war found the company in a critical position; either it would have to develop efficient manufacturing processes, or suffer enormous losses in apparently useless buildings and machinery. Intensive research proved to be the solution of the company's problem. The old-time method for producing phenol was discarded and a new process devised and placed in operation. The next steps were to undertake the production of the phenol derivatives, aspirin and synthetic oil of wintergreen, and to utilize the byproducts from indigo and phenol manufacture in making artificial flavors and perfumes. Aniline was produced by a new process based upon the action of ammonia upon chlorobenzene. An alloy of magnesium metal, weighing only one-fourth as much as iron, was manufactured in quantities for airplane parts, portable tools, high-speed machinery, and many other purposes. The company was the first to produce a spray material of organic origin which contained no arsenic or lead.

Without constant research the Dow Chemical Company could not have achieved such a record of accomplishments. Since 1919 when a group of organic research chemists was formed and an adequate reference library was established, there has been no let-up in the intensity of the company's research in many fields, including organic and inorganic chemistry, biochemistry, physics, and metallurgy. Today 225 graduate chemists and physicists, 270 technically trained engineers, and 170 laboratory assistants continue to work on problems new and old.

E. I. du Pont de Nemours and Company

In no company in the country have chemistry and chemical research played a more important part than in E. I. du Pont de Nemours and Company. The founder himself, E. I. du Pont, when 16 years old, had begun to study chemistry in the laboratory of Lavoisier, who was then in charge of the manufacture of gunpowder for the French Government. In 1837 the direction of the company fell to Alfred du Pont, who had been a former student of chemistry under Thomas Cooper at Dickinson College and who was always "contriving" a new instrument or experimenting in the laboratory in an effort to improve the quality of the powder made by the company.[95] Henry du Pont, who assumed the management in 1850, was not interested in experimenting with new methods and even wrote to various agents that he was satisfied that the powder could not be improved. The search for new methods and better products was continued, however, by Alfred du Pont's younger son, Lammot, a graduate of the University of Pennsylvania. In 1857, as a result of the latter's investigation, nitrate of soda was used in place of nitrate of potash in the manufacture of blasting powder, a substitution that not only benefited the company financially but also represented an advance in the art of powder making.[96] Before the Civil War he had accomplished much toward the development of both black and brown prismatic powders. In an attempt to carry out some "plant-scale experiments on the separation of nitroglycerol from the waste acid," for the purpose of recovering the latter, he was killed by an explosion. The loss of this able chemist was a serious one, but other members of the family carried on his work. By 1884 the company had succeeded in developing a brown prismatic powder which was satisfactory to the Government.[97] Francis G. du Pont, an efficient chemical engineer, invented and developed the du Pont smokeless powder and later, with the aid of Pierre S. du Pont and others, a smokeless powder for the Government's use.

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[95] Du Pont, Mrs. B. G. E. I. du Pont de Nemours and Company, a history—1802-1902. Boston, New York, Houghton Mifflin Co., 1920, pp. 72-73.

[96] E. I. du Pont de Nemours and Company, a history—1802-1902, p. 78. See footnote 95; Reese, Charles L. American chemical industries. E. I. du Pont de Nemours and Co. *Industrial and Engineering Chemistry, 17*, 1094 (October 1925).

[97] American chemical industries, pp. 1094-1095. See footnote 96.

For nearly a hundred years the du Pont Company applied chemical knowledge to improve the quality and increase the number of its products, but it was not until 1902 that scientific research became a clearly defined part of the company's policy. In that year the Eastern Dynamite Company, which controlled several other dynamite manufacturing companies, established under the guidance of Charles L. Reese the Eastern Laboratory in Gibbstown, N. J. Two years later the Experimental Station was established, and in 1906 it was installed in its present location near Wilmington, Del.

The Experimental Station was under the jurisdiction of the company's development department until 1911 when, together with the Eastern Laboratory, it became part of the newly created chemical department, which for the next 10 years directed all of the company's research. Although originally organized for research in explosives, the chemical department, following the general diversification and expansion of the company's business, soon extended its activities into such fields as dyestuffs, textiles, synthetic organic chemicals, heavy chemicals, and pigments.

Research had become such an important factor in the success of the company by 1912 that a United States court, in a decree which divided the company's business by establishing two independent competing organizations—the Hercules Powder Company and the Atlas Powder Company—stipulated that the laboratories of the du Pont Company should serve the two new companies for a period of 5 years. Back of this requirement was the fear of the court that new developments in the laboratories, unless made available, might prevent the success of the new companies.[98]

In 1922 a complete reorganization of the manufacturing, sales, and research activities of the company resulted in the decentralization of research, which today is carried on by nine major operating departments, two controlled subsidiaries, and the chemical department. The research work of the operating departments and the subsidiaries is concerned largely with their respective branches of industry and technology. The chemical department is concerned not so much with applied research problems as with the exploration of new fields of science and pioneering investigations aimed at the development of new products and processes. Thus, insofar as fundamental research and long-range research are concerned, the chemical department serves the entire range of the company's activities. Nylon, which represents a wholly new family of organic compounds of the class of polyamides, is a notable result of the fundamental research of this department. In the fields of explosives, powders, dyestuffs,

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[98] American chemical industries, p. 1095. See footnote 96.

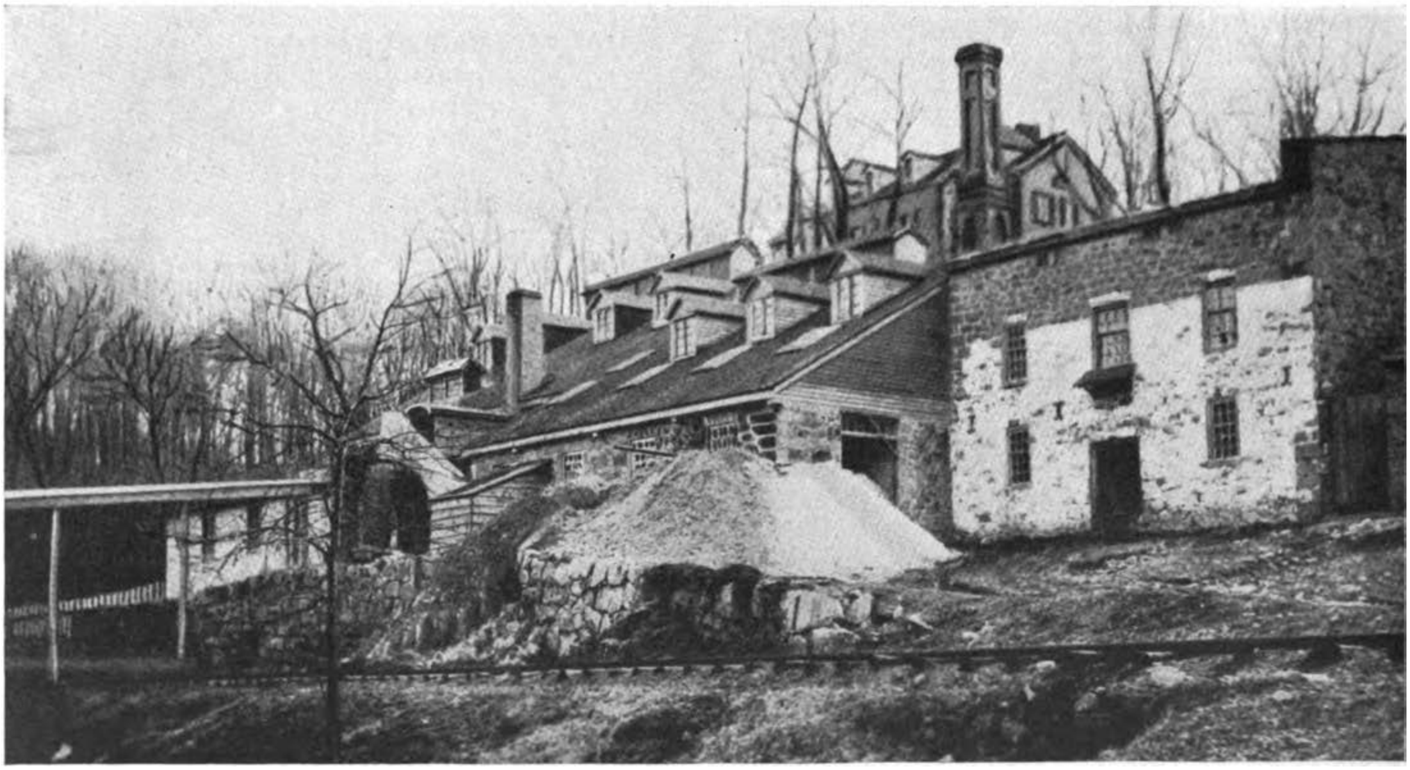

Figure 7.—The First Laboratory of E. I. du Pont de Nemours and Company, Incorporated, Was Housed in this Building, Erected About 1802, Wilmington, Delaware

cellulose film, cellulose nitrate lacquers, synthetic resin enamels, synthetic rubber, and camphor, the accomplishments of the various laboratories have been almost innumerable and their effect upon the industrial life of the Nation has been incalculable.

Monsanto Chemical Company

The Monsanto Chemical Company, established in 1901 to make saccharin, now produces a variety of products in the following three broad groups: fine and medicinal chemicals, heavy chemicals, and intermediates. An important factor in the company's growth, particularly in recent years, was its research laboratory, which was acquired in an unusual manner. In 1928, the Thomas and Hochwalt Laboratories, then 2 years old and engaged in commercial research in Dayton, Ohio, began work on the problem of producing synthetic resins from petroleum bases. After 5 years the study pointed to such important possibilities that the Monsanto Chemical Company purchased a major share in the development. A subsidiary, called the Monsanto Petroleum Chemicals, Inc., was formed to exploit the process, while the Thomas and Hochwalt Laboratories not only expanded their research in connection with this new enterprise, but also engaged in other work for the Monsanto Company. By 1936 so large a proportion of the laboratory's effort was being devoted to the company's problems that a merger was effected. That same year the company's expenditures for research were 3.04 percent of its sales and 16.5 percent of its net income.

Petroleum

Atlantic Refining Company

The Atlantic Refining Company began its corporate existence April 29, 1870, and during the next 30 years much work was done by various individuals of scientific and engineering attainments upon the problems of petroleum refining and the processes and machines involved in the packaging of petroleum. About 1900 the emphasis placed on research was increased, but investigations were still largely carried on in connection with operating work. In February 1924 a separate department was established under the title "Process Division"; later this title was changed to "Research and Development Department." In 1924 this department numbered 82 individuals and by December 1939 it had grown to 195. At the present time the department has well equipped research laboratories, including an automotive laboratory equipped with an electric chassis dynamometer and an air-conditioning apparatus which permits studies at temperatures 20° below zero, Fahrenheit. In the development branch, pilot units permit petroleum refining operations on a small scale, but in such a manner that results in the plant can be duplicated and anticipated.

Among those developments in the petroleum industry to which the company has made substantial contributions are the evolution of distillation processes from batch stills, through tower stills, to the modern pipe still for the large scale fractional distillation of crude petroleum; the solvent extraction of lubricating oils; the thermal production of motor fuels from both heavier and lighter hydrocarbons; and novel developments in the construction and propulsion of ocean-going tankers.

The Atlantic Refining Company also cooperates with both automotive and petroleum companies in projects conducted under the auspices of such national bodies as the American Petroleum Institute, the Society of Automotive Engineers, and the American Society for Testing Materials.

Gulf Research and Development Company

When the management of the Gulf companies decided to centralize its research activities, Dr. Paul D. Foote was called in August 1937 from the National Bureau of Standards to Mellon Institute, Pittsburgh, to head the new research program. The number of technical men employed at Mellon Institute to work on the company's production and pipe-line problems, trebled within a short period. In December of the next year offices were opened for work in geophysics. During 1929 a building was erected in Pittsburgh to house the new research activities. In January 1930 most of the company's employees at Mellon Institute and the geophysical group were transferred to the new quarters. Definite technical divisions of geophysics, engineering, chemistry, physics, materials engineering, and business management were set up as the research department of the Gulf Production Company. The total staff numbered about 90.

By 1937 the Gulf Research and Development Company had built several new buildings and had a laboratory staff of 418. An additional 575 employees were doing exploratory work in the United States and foreign countries.

Humble Oil and Refining Company

The Humble Oil and Refining Company started operations at its first major refinery in 1920. For the first 4 years there was no formal organization for research work, but there was, of course, a laboratory for the control of refining operations. Two or three of the better-trained men in this routine laboratory who showed an aptitude for special investigations were from time to time assigned to work on proposed processes and on the solution of plant operating problems. The refinery was growing rapidly, and in 1924, a separate group was set up to spend full time doing research and development work on refining processes. At the start, this group consisted of seven technically trained men, some of whom were transferred from the routine laboratory.

From 1924 to the latter part of 1926 all the research and development effort was associated with the current and contemplated refining processes at the Baytown refinery located about 30 miles east of Houston, Tex. In the latter part of 1926, a comprehensive research program on the production of alcohols and organic chemicals from hydrocarbons present in natural gas was initiated, and a separate unit with laboratory facilities and experimental equipment was established in north Texas, where natural gas supplies were readily available. At first this group consisted of 3 technical and 20 nontechnical men, but in the course of the work it was increased to 7 technical and 36 nontechnical men.

From 1929 to 1932 an extensive research program on hydrogenation was conducted at Baytown, but it was concluded soon after plans for the installation of hydrogenation equipment at Baytown were abandoned. The depression was about at its severest stage, and activities had of necessity to be reduced by roughly 40 percent. This reduction was accomplished partly by the release of assistants and service men without technical training and partly by decreasing the number of hours a month that each man worked. As economic conditions improved, the research activity was again expanded by increasing the working hours of each employee, until by the beginning of 1934, the force was back on a normal full-time basis. From then until 1936, the research and development continued on a fairly constant level, and no substantial additions were made to personnel. The period 1936 to 1938 was one of expansion, and the force was increased some 60 percent to 70 percent over the period. Since 1938, 10 men have been added to the staff.

Only a relatively small proportion of the research and development effort has been directed toward work of a pioneering type since the principal emphasis has been placed on improving correct refinery processes and products and on improving and adapting known processes to the particular conditions existing at the company's refineries. Since the company has access to the results of research work carried on by the Standard Oil Development Company, an intensive pioneering program is not essential. Nevertheless, its program of industrial research has enabled the company to operate its refining process at a high level of efficiency.

Convinced of the value of its research activities in oil refining, the company decided in the middle of 1928 to establish a separate unit for research on drilling and the production of crude oil and natural gasoline in the field.

The group of 22 technical men and 16 nontechnical men assigned to the production unit has made valuable contributions toward the answer to such problems as the estimation of reserves, well spacing, the chemical treatment of drilling fluids, the flow of oil, gas, and water mixtures through reservoir rocks, and the behavior of oil and gas reservoirs under various operating conditions.

A third research group has been engaged since 1925 in geophysical exploration. Discontinuing the refraction method in 1920, the company adopted the reflection technique and now has eight reflection parties operating in the field. Although in geophysics, emphasis has been placed upon practical research, some fundamental work has been done.

Shell Development Company

Previous to 1928 the plant engineers of the Shell Oil Company, Inc., made numerous improvements in oil technology, but a new era of planned research began in 1928 with the creation of the Shell Development Company. From the start its directors saw in research the means not only of bringing about the improvement and more economical processing of such staple commodities as gasoline, kerosene, fuel oil, and lubricants, but also of laying the basis of a profitable chemical industry through the study of petroleum as a primary raw material containing a great variety of hydrocarbons.

The policy of the Shell Development Company has been to undertake one project of research after another, developing each through the stages of fundamental research, applied research and semicommercial trials, to the final commercial application. Thus by a series of limited objectives, the company has evolved at its laboratories in Emeryville, Calif., a well-rounded program of research, which embraces all the major interests of the oil industry.

The Shell management intentionally created the Development Company as a separate unit freed from the day-to-day problems of operation so that is might plan and conduct research on a broad, long-term basis. The operating companies have laboratories of their own from which the technical controls of their operations are exercised, and in which many experiments for the improvement of operations are carried out. Occasionally research begun in the laboratory of an operating company, however, proves to be of such a fundamental character that it is transferred to the laboratory of the Development Company, and, conversely the Development Company, for geographic or other special reasons, sometimes transfers problems to the operating companies.

Although the work of the research laboratories has, by a combination of organization and natural growth, come to be arranged under such major departments as organic chemical research, application research, pilot plant research, oil production research, oil technology research, engine research, asphalt research, and fundamental research, a large degree of flexibility and cooperation is maintained. Approximately 15 percent of the total budget of the laboratories is spent upon such fundamental investigations as the mechanism of catalysis, mechanism of polymerization, hydrocarbon rearrangements, and pyrolysis.

The laboratory of the Development Company, starting with a total staff of 57 including 12 university-trained research workers, has steadily expanded until in 1940 it employs 520 persons, of whom 91 are senior research workers and 260 are university graduates.

Standard Oil Company of California

Organized research and development work was initiated in the Standard Oil Company of California in 1920 when a research division for these activities was created within the manufacturing department. During the first few years, the main effort of the division was directed towards the improvement of such refining processes as distillation, thermal cracking, acid treating, and acid recovery, with such impressive returns that in 1926 the research work was expanded and centralized in an independent department. Since that time the department has grown steadily until it is now composed of a staff of 400 men, about half of whom are chemists, engineers, physicists, or men with some technical training. Two branch laboratories are maintained, and the department has representatives at the various refineries and producing plants.

The company has done pioneer work in the manufacture of compounded lubricating oils for Diesel engines, and in recent years much of its research has been done in the field of catalysis for the purpose of developing processes by which petroleum can be converted into new and better products for industrial and domestic uses.

Standard Oil Company of Indiana

Research in the Standard Oil Company of Indiana has expanded in a period of 50 years from the work of a single plant chemist to the multiple activities of a modern department comprising 186 technical and 250 nontechnical men.

Research began in the company in 1890 with the hiring of Dr. William M. Burton to investigate the Frasch Desulfurization Process. Later, when the largest refinery of the company was being erected in Whiting, Ind., Burton established an analytical laboratory there to test paints and other materials being used in the construction. During the next 20 years, until 1910, there was little increase in the laboratory staff, which was mainly concerned with routine analyses. Some development work was carried out, however, and it resulted in improvements in the manufacturing of asphalts, greases, lubricating oils, and candles.

The years 1910–20 brought moderate expansion in both personnel and research. Although emphasis continued to be placed on analytical work, experiments were carried out in connection with the Burton cracking process, while other investigations led to improvements in the manufacture of medicinal white oils and lubricants.

After 1922 the expansion of the laboratory staff was rapid, conforming to the widening of research activities. The laboratories of 3 refineries of the company were incorporated into the research department, while other laboratories were established. One, the engine research laboratory, was founded in 1925; another was organized early in the 1930's for fundamental research. The increase in the total personnel was twentyfold in 20 years.

Paralleling this structural growth were the extended activities in and accomplishments of research. With the introduction of the approach of chemical engineering to refinery problems, studies were made of distillation, fuel economy, corrosion, evaporation losses, and gasoline recovery. Considerable effort was also expended in the development of thermal cracking, both in the field and in experimental equipment in the laboratory. From the intensive research on thermal cracking, the large modern combination cracking unit was evolved and has since been continually improved to a point where it is capable of producing better than 75 percent of high octane gasoline from crude oil. The problems of knocking characteristics and gum formation, arising from the application of the thermal cracking process to meet the growing demands for gasoline, were solved by experiments with antioxidants. The processes of propane dewaxing and chlorex extraction resulted from intensified research on lubricating oils.

At the present time experimental work is being carried out on all phases of petroleum refining from the crude distillation to the road testing of fuels in modern automobile engines. In addition, considerable effort is being expended in the development and improvement of specialty products such as greases, candles, asphalts, road oils, solvents, special lubricants, and domestic fuels.

The activities of the research department are coordinated with those of its closely associated development and patent department, which assists in maintaining technical contacts with competing companies and other industries, provides a technical information service, and manages the patent affairs of the company.

In addition to the research and development activities conducted directly by the staff, the company has contributed to and participated in cooperative research projects conducted under the sponsorship of the American Petroleum Institute, Gasoline Products Company, The Polymerization Processes Corporation, and The M. W. Kellogg Company.

Standard Oil Company of New Jersey

Centralized industrial research in the Standard Oil Company of New Jersey began in a modest way with the organization of the development department in September 1919. The technical staff of this new department consisted of 26 analytical and research chemists in the research laboratory, and 3 chemical engineers in the experimental division. In addition a general engineering department of some 60 men worked in close collaboration with, but not as an integral part of, the development department.

The rapid technical advance in methods of cracking and the growing use of more efficient fractionation equipment by the petroleum industry were accompanied by an expansion of the experimental division, and a small increase in the staff of the research laboratory of the development department, which, by the end of 1926, had a total personnel of some 150, including chemists, engineers, and nontechnical assistants. Motor fuel and lubrication laboratories were established in the early 1920's for testing and developing improved fuels and lubricants.

Standard Oil Development Company

The Standard Development Company was incorporated in Delaware in September 1923 as a patent-holding and licensing organization. Its corporate name was changed to the Standard Oil Development Company in October 1927, and the new company took over the research and development activities previously carried out by the development department of the Standard Oil Company of New Jersey. The general engineering department and the standard inspection laboratory were incorporated into the new organization.

In December 1927 the motor fuel laboratories were enlarged and the refining research group (process laboratories) moved into new quarters. The facilities then made available to the refining research group consisted mainly of pilot plant equipment and permitted a more systematic study of refinery processes, thermal cracking, atmospheric and vacuum distillation, and acid and solvent treating. This work was carried out on a scale large enough to secure basic data for design of new equipment.

Early in 1927 negotiations, begun in 1925 with the owners of the Bergius and Pier patents on hydrogenation, culminated in the acquisition of the American rights to this process by the company. Shortly after this agreement was reached a hydrogenation laboratory was established. The research and development work of this organization led to the commercial application of the hydrogenation process to petroleum distillates and heavy residues. Thus it became possible to make high quality fuels and lubricants from feed stocks which could not be utilized by existing processes.

The Hydro Engineering & Chemical Company was incorporated as a subsidiary of the Standard Oil Development Company in February 1930 to supervise development work on hydrogenation and to design hydrogenation plants in the United States. Including this newly formed unit with a staff of 67 engineers, the Standard Oil Development Company had approximately 600 employees by the end of 1930.

The company completed a new research laboratory in 1931 to provide much needed facilities for the technical library of the patent department. This library has one of the largest technical reference sections in the petroleum industry and a staff which keeps the research, development, and engineering groups informed concerning the latest advances in the petroleum and allied fields.

The staff of the comapny increased rather rapidly to approximately 1,000 persons by the end of 1937. Subsequent additions to the staffs of the various laboratory and engineering groups have gradually increased the personnel of the Standard Oil Development Company to its present 1,300 employees.

The Standard Oil Development Company by agreement with the major refining units of the Standard Oil Company of New Jersey acts as a central research and development agency for the operating companies. Such centralization of research work prevents unnecessary duplication of staffs and laboratories and results in much better research facilities than would be possible had each operating group tried to proceed independently.

Universal Oil Products Company

In 1907 Jesse A. Dubbs, owner of the Sunset Oil and Refining Company and the Globe Asphalt Company of Obispo, Cal., was faced with a serious problem. One of his oil wells had developed water which could not be separated from the oil by simple heating in a pipe still, the process which he had been using on other emulsified crude oils. After 2 years of investigation and experiment, he solved the problem and applied for a patent. Dubbs had discovered the first heat cracking process, but he did not realize it until 1913, when Dr. William M. Burton secured a patent on another heat cracking process. Dubbs then amended his application, and when his patent was issued, in 1915, it covered cracking and condensation under the pressure of self-generated vapors.

A group of men interested in the commercial possibilities of the patent acquired it, established a laboratory at Independence, Kans., and engaged a staff of research workers, including Carbon Petroleum Dubbs, son of the inventor, to develop the cracking process. From this beginning the Universal Oil Products Company has grown to be an important research and development organization.

The investigations made at Independence resulted, in 1919, in the building of a cracking unit which, in a spectacular run lasting 10 days, demonstrated the possibilities of the process. Because of the formation of coke in the tubes of the cracking unit, runs had previously been limited to 2 days. Successful as this demonstration was, it served only to stimulate the company to a greater research and development campaign. J. Ogden Armour supplied funds, to the extent of more than $6,000,000, for the work.

The laboratory at Independence was soon insufficient for the company's needs, and, in 1921–22, a new one was built at Riverside, Ill. In addition to the laboratory buildings the research equipment now includes 25 acres of tanks and "strange looking structures." Dr. Gustav Egloff directs the activities of approximately 250 research workers, most of whom are men trained in science and engineering. The staff is divided into groups of specialists such as mathematicians, physicists, physical chemists, and organic chemists. Other even more specialized groups work upon the specific problems of catalysis, treating, and cracking. Fundamental research has led to such developments as Ipatieff's catalytic polymerization process, which bids fair to become the forerunner of a whole group of new processes, and Morrell's alkylation process, by means of which 100 octane gasoline is produced.

In East Chicago, a few miles from the laboratory, the company maintains a 1,000 barrel cracking unit in which new developments, after they have been tested in a pilot plant and on a semiworks scale, can be tried on a commercial scale before being offered to prospective licensees. The results of the company's research and development are made available not only to those who operate equipment under a license but also to the industry as a whole, as soon as this step can be taken safely.

In addition to research in its own laboratories, the company has helped to finance the work of the American Petroleum Institute and has maintained research fellowships in several universities and technical schools.

Electrical Communication

Bell Telephone Laboratories

On March 10, 1876, Alexander Graham Bell's voice was transmitted to the ear of his assistant, Thomas A. Watson, over a wire strung between 2 rooms on the top floor of a boarding house in Boston. The patient research of another pioneer, who had often been beset with poverty, had met with success; and the public, in spite of its skepticism, was soon to have a new means of communication. Gardiner G. Hubbard, Bell's father-in-law, organized the Bell Telephone Association, in partnership with Bell, Watson, and Thomas Sanders, the father of one of Bell's deaf pupils. In May 1877 a man from Charlestown, named Emery, came to Hubbard's law office and handed him $20 for the lease of 2 telephones. The world's first commercial telephone bill had been paid in advance. A crude exchange was established, and 6 telephones were lent to the proprietor of a burglar-alarm system for installation in 6 Boston banks. Within 90 days, 778 telephones were in use.[99] Although faced with many struggles, financial, legal, and technical, the new telephone industry was gathering momentum.

Without continuous research, however, the present system of communication by telephone could never have been achieved. Since the days when Bell and Watson constituted the "Department of Development and Research," men have sought knowledge that would improve and extend this means of communication. Previous to 1907 the Bell Telephone System had three laboratories or departments of development and research, one in the American Company at Boston, one in the Western Electric Company at Chicago, and one in the Western Electric Company at New York.[100] To promote efficiency and economy the laboratory work and the experimental work of these three groups were combined in 1907 into a single unit, known as the Engineering Department of the Western Electric Company.

Increasing the distance spanned was from the beginning one of the outstanding problems of telephony. From this combined laboratory organization came a new attack on this basic problem, and telephone service was opened in 1911 between New York and Denver, a distance of 2,100 miles. This step was largely accomplished by improvements in the construction and application of the loading coil which had been invented at the turn of the century.

Several years before the New York to Denver service was opened, however, the company's engineers realized that unless the problem of telephone repeaters could be satisfactorily solved, this line would mark the practical limit of distance for telephony.[101] Consequently, J. J. Carty, then chief engineer, of the American Telephone Company asked for money and men to develop, by further research, a telephone repeater suitable to operation on long loaded lines. Theodore N. Vail, president of the company, approved; consequently:

> in the winter of 1910–11, a small group of scientists was selected and research initiated under the general guidance of Dr. F. B. Jewett, who was then Transmission and Protection Engineer of

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[99] Kaempffert, Waldemar. A popular history of American invention. New York, C. Scribner's Sons, 1924, vol. 1, p. 330.

[100] Gifford, W. S. The place of the Bell Telephone Laboratories in the Bell system. *Bell Telephone Quarterly*, *4*, 90 (April 1925).

[101] Mills, John. The line and the laboratory. *Bell Telephone Quarterly*, *19*, 5 (January 1940).

the American Telephone and Telegraph Company. The men who were to investigate the problems which loaded lines presented to repeaters were in Dr. Jewett's department in the telephone company; those who were to make a laboratory attack on the repeater itself were grouped into a research department under Dr. E. H. Colpitts in the Engineering Department of the Western Electric Company. The scientists thus assembled became the nucleus of the present Research Department of the Bell Telephone Laboratories. A year later Jewett became Assistant Chief Engineer of the Western Electric Company, and in that position coordinated the entire transcontinental line research, whether carried out in the laboratory or in the field.[102]

The work was directed primarily to the development of electrical amplifying devices, to improvements in line structure, and to the proper association of line and amplifiers at periodic intervals to give stable operation. Although several forms of repeaters were tried out successfully on the line, it was demonstrated that the vacuum tube could be perfected to be the most effective telephone amplifying device. As a result of the work, on January 25, 1915, Alexander Graham Bell in New York talked with Thomas A. Watson in San Francisco over 3,400 miles of wire.

Since that time have come in succession improved repeater operation over open wire lines, repeated cable systems adequate to span any distance, multiplexing of both open wire and cable circuits, and the multichanneled coaxial circuit type of cable now going into use. The development of transoceanic radio telephone service to Europe and later to all parts of the world has been the final step in extending the distance range of telephone communication.

Since the laboratory had become so important and its work so extensive by 1925, it was given corporate form and became known as the Bell Telephone Laboratories, Inc. Dr. Jewett was made president of this unit and a vice president of the American Telephone and Telegraph Company, which owns the Laboratories jointly with the Western Electric Company. The Laboratories are responsible to the former company primarily for fundamental research and development, and to the latter for development, design, and engineering in connection with manufacture.

The principal activities of the Bell Laboratories are carried out in a headquarters building in New York City, together with leased space in two other city buildings. However, many kinds of development are carried out in smaller country locations. These include radio laboratories at Holmdel, Deal, and Whippany, N. J., a chemical laboratory at Summit, N. J., an outside plant laboratory at Chester, N. J., and a transmission testing station at Phoenixville, Pa. Stations are also located at Gulfport, Miss., and Limon, Colo., to insure a range of climatic conditions for testing of preservatives for timber products. In addition, small groups of people from the laboratories are located at the Western Electric factories at Kearny, N. J., Hawthorne, Ill., and Point Breeze, Md., and at a large number of places throughout the country, to carry on work with the people and plant of the operating telephone companies.

About 2,000 out of a total of 4,600 people in the Bell Telephone Laboratories are professionally trained members of its technical staff. This trained personnel covers development and engineering as well as research. Somewhere between a fifth and over a half of the personnel would be designated as "research" according to the interpretation of that somewhat indefinite term.

Since research, development, manufacture, and operation are all included in the Bell System organization, the diversity of problems covered by the Bell Telephone Laboratories is peculiarly wide. Much of the Laboratories' work finds embodiment as operating systems of apparatus—transmission systems for handling telephone currents and switching systems for establishing telephone connections. The work of such a system starts with fundamental investigations of materials and of electrical and mechanical action, together with studies of the needs and experiences of the operating companies. The work continues through the model stage of apparatus and functioning combinations, and then into the economical design of all the parts involved and their association into an economical operating system. Included are considerations of manufacturing methods, factory testing, and field installation and operation. The development responsibility for the new system covers also its trial installation and tests of performance in the operating plant. The Laboratories' interest in the system extends throughout its useful life and may finally end with a consideration of the best way of obtaining any residual value as it goes to the junk pile.

The following statement, by one intimately connected with the Laboratories for many years, gives another picture of the diversity of the Laboratories' activities:

> Our research problems are scattered along the whole frontier of the sciences which contribute to our interests, and extend through the fields of physical and organic chemistry, of metallurgy, magnetism, electrical conduction, radiation, electronics, acoustics, phonetics, optics, mathematics, and even of physiology, psychology, and meteorology. In each field inquiry carries the important question of its practical applications, and thus involves consideration of the specific devices which our industry uses and study of new forms into which they may be molded and new services which they may be made to render.[103]

Western Union Telegraph Company

For many years after the demonstration of the practicability of Morse's electric telegraph, research and development in the field of electrical communication

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[102] The line and the laboratory, p. 10. See footnote 101.

[103] Arnold, H. D. Organizing our research. *Bell Laboratories Record*, *2*, 161 (June 1926).

were carried on almost entirely by individuals. Although many important improvements in repeaters, the duplex, the quadruplex, and the telephone resulted from the work of these individuals during the early years of the telegraph industry, it was not until about 1900 that any concerted effort was made to organize telegraph research and development. About that time the nucleus of a Western Union laboratory existed in New York, masquerading under the name of a "Repair Shop." But to all intents and purposes it was a laboratory, for there in a space of about 40 by 100 feet were assembled the best of machines and apparatus then available for experiments with telegraph equipment. The activity in this shop proved so worth while that a year or two later the company decided to establish an Electrician's Work Shop, and there six men were regularly employed in experimental and development work. Compared with present-day apparatus their equipment was crude, but with it much of the ground work upon which modern telegraph practice rests was done.

Despite these limitations of space and equipment, the first units of the modern multiplex, which permits the simultaneous transmission and reception of several messages over a single wire, were being tested and perfected, and the first of the modern telegraph printers was being developed. The successful application of the combination of multiplex channels and printing telegraph marked the beginning of the era of mechanized telegraphy to which these laboratories have made and are still making major contributions.

In 1916 the first laboratory to be organized as such by Western Union was established at 16 Dey Street, New York, and about 15 men were employed. This laboratory had some of the equipment which is now considered indispensable, including an oscillograph, a fair selection of meters, electrometers, galvanometers, and Wheatstone bridges, as well as a small power plant.

Late in 1916 the laboratory was moved to more spacious quarters. The staff was increased to 25 engineers and organized into 5 divisions—cable, power plant, apparatus, automatics, and general laboratory. Demands upon the laboratory continued to increase, and in 1918 a research and a chemical laboratory were added. In 1921 a laboratory devoted to the development and improvement of the multiplex and simplex was established; a year later a mechanical laboratory was added.

The rapidly expanding telegraph business required, however, still more experimental and development facilities, and in 1925 the laboratories again were moved to larger quarters. Work upon cables, simplex printers, tickers, and the multiplex continued to increase. Moreover, investigations in chemistry, metallurgy, and photography were made necessary by the company's broad program of research which sought not only to bring the benefits of scientific knowledge to every branch of the telegraph industry, but also to make sure that its vast volume of supplies was of suitable quality.

Twice since 1925 the quarters devoted to research have been outgrown, and in addition to the laboratories in New York the company maintains another laboratory at Water Mill, Long Island, which is designed to deal primarily with the many problems presented by the radio industry. Work is also done there upon problems relating to wire telegraphy, such as the synchronous operation of telegraph equipment, the balancing of ocean cable circuits, and facsimile telegraphy. While Western Union research aims primarily to improve telegraph service and to lower costs, it frequently leads to devices and products that are made available to other industries.

Electrical Machinery, Apparatus, and Supplies

General Electric Company

During the last part of the nineties the electrical industry had been expanding with tremendous speed. New and larger stations were springing up in all parts of the country, and transmission lines were being strung to carry the increasingly higher voltages. The constant demand for larger and larger apparatus with which to generate, control, transmit, and distribute the steadily increasing amounts of power forced innumerable problems upon the company's engineers. As difficulties arose, and as new ideas came, they were handled in the department most intimately concerned. To a limited extent facilities were also provided in the model department for working out new problems, but the personnel of the department was generally very limited, and the magnitude and importance of the problems undertaken soon became restricted.

The works laboratory of the early days of the industry has been described by Elihu Thomson as—

> not necessarily for research, but for the examination of products brought in or sent out, and for the analysis of materials. We may picture . . . a space set aside from a portion of the manufacturing and testing department, where with a few tools and perhaps one or two workmen, devices and new appliances were constructed in the form of working models, which were there to be refined and immediately put into manufacture. Sometimes this space was limited in extent to that of a single moderate-sized room, and later on, for privacy, it might be a space partitioned off from the rest of the floor.[104]

With the industry in its infancy, such activities were sufficient to meet the immediate demands of the business, but as the various departments became more distinct, as the number of products increased, and as the quantity of products produced became greater, little attention could be given to scientific research. But

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[104] Thomson, Elihu. In an unpublished manuscript.

several individuals in the General Electric Company—unwilling to accept the point of view of a financier in the textile industry who told Elihu Thomson that he thought the electrical industry was rapidly becoming standardized and getting to the point where new research and experimentation were hardly necessary—were convinced of the need for a continuous search for new scientific knowledge. They had heard of the work being done by Cooper Hewitt on the mercury arc lamp and felt that they, too, should investigate it.

By 1899 the period of business stagnation following the depression of 1893 had largely passed, and business men were again viewing the future with optimism and making their plans accordingly. Mr. E. W. Rice, Jr., was at this time technical director of the company. He had been a student under Elihu Thomson and later his assistant when the latter had left teaching to direct his energy to the commercial development of his many ideas. Both men saw the necessity for new facts and principles in the electrical industry, and both men felt it futile to wait for those facts to come from the universities. Their idea of supplementing the company's existing engineering and development facilities with a research laboratory was also enthusiastically supported by Dr. Steinmetz and Mr. Albert G. Davis, the company's patent expert. With such backing, Rice was able to persuade the directors to grant him an appropriation to provide facilities and personnel for a systematic program of research, and the annual report for the year 1901, carried the announcement to stockholders that—

> although our engineers have always been liberally supplied with every facility for the development of new and original designs and improvement of existing standards, it has been deemed wise during the past year to establish a laboratory to be devoted exclusively to original research. It is hoped by this means that many profitable fields may be discovered.

The most important step was still to be taken—the hiring of a man capable of organizing and guiding a research laboratory of the type contemplated by the directors of the company. Since there were no outstanding research men in other industries to be called to General Electric, the company turned to the Massachusetts Institute of Technology. There Rice found Dr. Willis R. Whitney, assistant professor in the chemistry department. Pleased with the reports of Whitney's energy, originality, and skill, Rice and Steinmetz went to Boston, talked with Whitney, and asked him to undertake the work at Schenectady. Whitney was not anxious to leave Boston, for, as he expresses it, "I was having too much fun working on colloids and didn't want to stop." But this was not Whitney's only misgiving; he was also a bit doubtful as to whether or not he could find enough work at Schenectady to keep him busy. Rice, convinced that he had found the right man, was equal to the situation. He surprised Whitney by telling him to bring his work on colloids with him, and if by any chance he found he did not have time to work on them, he could get somebody to help him. To meet Whitney's second objection that there might not be enough for him to do, Rice proposed an arrangement whereby Whitney would spend part of his time at Schenectady and part at the Massachusetts Institute of Technology. In September 1900 Whitney began a 3-year period of long-distance commuting. From Monday morning until Wednesday night he worked in Schenectady; the rest of the week he spent in Boston. At the end of 3 years, however, convinced that there was enough to do in the research laboratory of the General Electric Company, he left his teaching position.

For many years, Whitney has had as his associate at Schenectady Dr. W. D. Coolidge, who likewise began his career in a laboratory at the Massachusetts Institute of Technology. When, in 1905, Whitney needed another man on the staff he decided to get Coolidge, of whose ability he was sure. The steps that followed must have brought at least an inward smile to Whitney. At first Coolidge was not interested. He did not care to leave either Dr. Noyes, with whom he was working, or the problem of "electrical conduction in aqueous solutions at high temperatures," which he was studying. Rice's tactics, this time used by Whitney, again won for the General Electric. Coolidge was told to bring his work right along to Schenectady, and there he could give all the time he wished to his aqueous solutions. Somewhat doubtfully he accepted the offer, but once in Schenectady his eyes must have sparkled when the innumerable intriguing and important problems which faced the small group of workers began to be known to him. It was not long before his aqueous solutions were shipped back to the Massachusetts Institute of Technology. Within 3 years he was assistant director of the laboratory. Of his many accomplishments the two best known are the Coolidge X-ray tube and ductile tungsten, on which he spent nearly 4 years of persistent and resourceful search before it was produced commercially. Since Whitney's retirement in 1932, he has directed the activities of the laboratory.

Mr. Rice's idea, from the very first, was to develop a laboratory for research in pure science. He wished it set sufficiently apart in the company organization to be free from the responsibilities of current problems of the company. Since in practice such detachment has been impossible to maintain, the rule in the General Electric Laboratory has been to give calls for assistance from the engineers and production men "precedence over all else claiming the attention of the staff, if they involve, as they usually do, possible loss to the company or delay in satisfactorily meeting a customer's needs." Nevertheless, one of the outstanding characteristics of the laboratory has been the director's constant effort to keep in progress as much fundamental research as possible. The fact that the laboratory has been free from all direct responsibility for engineering and manufacturing operations has made it less difficult to maintain fundamental research than it otherwise would have been. The presence of Dr. Irving Langmuir has also helped to keep fundamental research from being crowded out. Dr. Whitney, writing of Langmuir, said:

> Some promising research men are so tempted by urgent calls of manufacturing difficulties that they metaphorically divest themselves of their protecting clothing and quickly plunge into depths of factory troubles unfathomed by all previous experts. Not so Langmuir! He was destined to be a good helper (or life preserver), but a still better pioneer. His methods develop principles of new utilities instead of putting patches on the old.[105]

That scientists inevitably are led at times from research to its application because they alone have the knowledge necessary for design and development is shown by the following instance related by Mr. Larry A. Hawkins, executive engineer of the laboratory.

> When Langmuir had discovered the pure electron discharge from a hot cathode in high vacuum, Coolidge perceived and demonstrated the possibility of utilizing such a discharge in a new type of X-ray tube. He could not stop there if the new tube were to be made available to the medical profession. No other department of the company had the knowledge and facilities necessary for its design and development. Coolidge became for the time a designing engineer. Even when he had produced a tube satisfactory for the doctor's use, he had not completed the necessary task. No factory department was in a position to undertake its manufacture. Coolidge therefore had next to become a production manager, devising and building equipment, establishing details of material specifications, fabrication of parts, assembly, exhaust, and testing, and supervising the small scale manufacture, until others had acquired the necessary training to enable them to carry on.[106]

When Dr. Whitney decided that the activities at the General Electric laboratory were sufficient in number to require his full-time attention, he had about a dozen helpers. Since that time the increase in the number of employees has in general followed the increase in the company's business. Moreover, as the activities and accomplishments of the laboratory became more numerous, its prestige increased, and it was accorded greater independence. In 1903 a Research Laboratory Advisory Council had been formed, with Mr. Rice as chairman. For 12 years it held meetings two or three times a year in order to guide the development of the laboratory in a way that would be of greatest benefit to the company. Although Dr. Whitney, as director, had long enjoyed an entirely free rein, he continued to report the activities of the laboratory to the vice president in charge of engineering until 1928, when he was himself made vice president in charge of research. With this move the research laboratory took its place in the organization chart on a level with the major activities of the company.

Occasionally the laboratory staff has been decreased because of prolonged business depressions; but much more frequently by the transfer of a group of laboratory men to another department because of the development in the laboratory of a new product, so different from the company's prior commercial products that no existing department was competent to complete its development and carry on the initial manufacture. Such products as the new type of carbon brush for railway motors and other apparatus, ductile tungsten and the process of making it, the Coolidge X-ray tube, and the radio power tube have resulted in the organization of new departments manned by the men from the laboratory who had been in charge of the development and initial production.

With the exception of 2 or 3 years during the recent depression, the company has for 15 years followed the practice of inviting a carefully selected list of postgraduate students to work in the laboratory during the vacation period. As a result, the company, when in need of additional men, has been able to select those who have shown clearly that they possess the qualities necessary for a successful career in research.

The research laboratory cooperates closely with numerous other laboratories maintained by the company.

> There is the General Engineering Laboratory, specializing on the standardization of instruments and testing methods, the development of new instruments and new testing procedure, and the conducting of special engineering tests. There is the Thomson Research Laboratory at Lynn, from which have come fused quartz, the supercharger for aeroplanes, and a number of other developments. Each of the larger works has its own works laboratory, responsible for supplying the technical assistance and supervision required in factory processes, making physical and chemical tests on materials and product, conducting the necessary experiments for solving the day-to-day problems arising from factory operations or engineering requirements, and developing new factory equipment and processes. There is a large laboratory for lamp development, a metallurgical laboratory specializing on tungsten, molybdenum and their alloys, a lighting research laboratory, an illuminating engineering laboratory, and a high-voltage laboratory for studying lightning and other high voltage phenomena.[107]

If all of the laboratory work of the company were consolidated in the research laboratory, its staff would need to be increased manyfold, and the portion of its activities devoted to fundamental research would be a minute fraction of the whole and in constant danger of

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[105] Whitney, Willis R. Irving Langmuir, scientist. *Current History, 37*, 705 (March 1933).

[106] For this quotation and much of the factual material concerning the General Electric Co., the author is indebted to its executive engineer, Dr. Larry A. Hawkins.

[107] Hawkins, L. A. Manuscript.

being squeezed out entirely by the pressure of service work. Under the existing organization the research laboratory keeps as free from development and service work as it possibly can by turning over to the other laboratories as much of that work as they are prepared to take.

Today the total personnel of the research laboratory numbers 290. Thirty-four chemists, 17 physicists, 26 engineers, and 10 metallurgists are at work seeking both new knowledge and a better application of that already at hand.

Westinghouse Electric Company

Westinghouse Electric Company research started, in an unorganized way, with the formation of the company in 1886, and many technical developments took place between that date and 1902 (or 1903) when a research department was established by C. E. Skinner. Since the company then had no central laboratory, experimental work continued to be conducted in laboratories scattered throughout the East Pittsburgh Works. In 1916, however, a separate research building was constructed, and staffed with research scientists drawn from universities, from industry, and from their own laboratories in East Pittsburgh. To a considerable extent these men were occupied with fundamental and long-range problems, while the men in the older laboratories worked upon more immediate problems.

After the separate research building was completed, the lamp company research was housed there until it became evident that this work could best be carried on nearer the lamp works. For the past 20 years, therefore, lamp research has been a separate activity at Bloomfield, N. J., under the direction of Dr. H. C. Rentschler.

With the facilities provided by the new building and with the demands created by America's entry into the war, research expanded rapidly. The company was immediately involved in problems intimately connected with the military and naval needs of the country.

Many major developments in the electrical industry have come largely or entirely as a result of Westinghouse research. George Westinghouse himself was a pioneer in the generation, transportation, and distribution of alternating current. Machine-wound coils and laminated cores for transformers; air ventilated and oil filled transformers; the polyphase induction motor, invented by Nicola Tesla; the slotted armature for direct-current machines; the Scott transformer; and the synchronous condenser; these are some of the improvements contributed by research workers and engineers in Westinghouse. Micarta, a laminated plastic material widely used in the electrical industry for many years, originally consisted of paper and shellac, but men in the company's laboratory found that synthetic resins could be advantageously substituted for the shellac. Mr. C. E. Skinner, the first director of research at Westinghouse, was one of the first to make

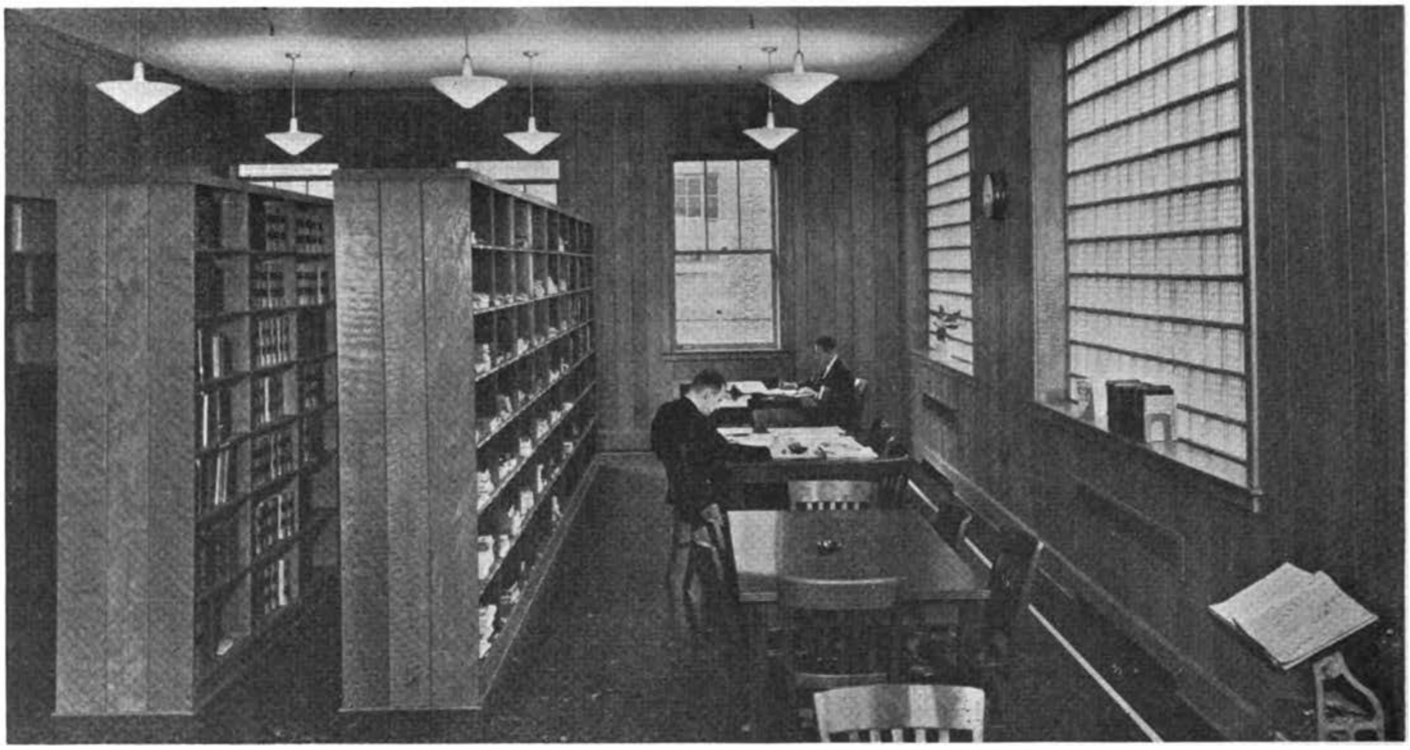

FIGURE 8.—Library, Research and Development Laboratories, Bakelite Corporation, Bloomfield, New Jersey. (Unit of Union Carbide and Carbon Corporation)

use of Bakelite and similar compounds in the electrical industry. In fact Westinghouse gave Dr. Baekeland his first commercial order for Bakelite. Improvements in insulation materials and electrical sheet effected in the laboratory have brought great savings to the users of electricity. New and valuable alloys, including one with the same expansion characteristics as hard glass and another of very great strength at high temperatures, which is a satisfactory substitute in many places for platinum, have been developed by the company. The laboratories have also played an active part in perfecting radio transmitting and receiving equipment. Some 10,000 of the tubes used in the early receiving sets were manufactured by members of the research staff.

In 1936 the company began an extensive program of research in the field of nuclear physics, which led to the construction of a 5,000,000-volt atom smasher of the electrostatic type. Another step toward more fundamental research was taken in 1936 when the Westinghouse Research Fellowship Plan, by which five Fellows with Ph. D. degrees would be appointed each year to carry on research in fields of their own choosing, was inaugurated at the suggestion of Dr. E. U. Condon. Fellowships are granted for 1 year, although they may be renewed for a second year, and, in general, the studies made by the recipients have no immediate commercial objective but are designed to increase the store of scientific knowledge.

Westinghouse supplements research in its own laboratories by maintaining a number of research fellowships and by subsidizing certain studies in such institutions as Mellon Institute, Arthur D. Little, University of Pennsylvania, Stevens Institute of Technology, Carnegie Institute of Technology, Massachusetts Institute of Technology, and the Engineering Foundation.

Rubber

B. F. Goodrich Company

Although Charles Goodyear discovered the secret of vulcanization in 1839, when he dropped a piece of rubber mixed with sulfur on the hot stove in his kitchen, it was not until 1895 that the first research laboratory in the rubber industry was established by the B. F. Goodrich Company at its plant in Akron, Ohio. Charles C. Goodrich, the eldest son of the founder, was a graduate chemist and the first manager of the laboratory.

As the uses for rubber grew, an ever-increasing number of problems were presented to the laboratory staff. Groups were organized to find methods of controlling and improving the raw materials, to study ways of bettering processes and equipment, and to develop new products. Their research uncovered the fact that certain organic chemicals added to rubber compositions shorten the time of vulcanization and improve the strength and aging properties of the finished goods. This advance made it possible for manufacturers to produce in greater quantities without building additional plants and for consumers to have better products at lower cost.

From the laboratory came also the discovery that carbon black, when incorporated in rubber goods in amounts much greater than had previously been used, increased the resistance of rubber to abrasive wear and made possible the construction of a satisfactory tread for automobile tires. Similarly the addition of certain chemicals to rubber, was found to retard its deterioration and to increase its resistance to heat and to cracking under repeated flexing.

At the present time the division of synthetic research under the direction of Dr. Waldo L. Semon, is particularly active in developing a rubber-like product made entirely from raw materials available in this country. Petroleum, the base, is broken down to butadiene, which is liquified, mixed with other ingredients prepared from natural gas and air, and then made into a milky emulsion by the use of soap supplied from American agricultural sources.

United States Rubber Company

As in many other great industries so, too, in the tire industry progress in the early days was the result of inventive genius. While this force is still important as the industry continues to grow, it has to be supplemented with systematic investigations of the factors in the manufacturing process which affect the properties of the finished product.

In the United States Rubber Company organized research is conducted by the operating divisions of the company, in each of which there is a development department with suitable laboratory facilities, and by the general development division, of which the general laboratories are a part. Fundamental research and such applied research as is of interest to more than one division are carried out by the general development division. Responsibility for the maintenance and improvement of the quality of the company's products rests upon the technical groups in the operating divisions. This separation of responsibilities permits both the necessary concentration upon research and the proper attention to manufacturing processes.

For years the company has studied systematically the physical and engineering problems involved in the manufacture of tires, and as a result has contributed materially to the progress which the industry has made in increasing the safety, improving the performance, and lengthening the life of this important product.

Although it had been known for a long time that certain materials would accelerate the process of vulcanization, only within the last 20 years has the company been particularly active in discovering and promoting the use of chemicals for this purpose. During the same period the useful life of rubber products has been greatly increased by the development of another class of chemicals known as antioxidants.

About the time of the First World War, the United States Rubber Company began an intensive study of latex in an effort to find methods of using it in manufacturing operations in place of dry rubber. As a result of this study the company has developed a number of new or improved products which can be manufactured by using the latex method.

Among the new products are a rubber thread which when covered with textile yarns is known as Lastex; a latex paper widely used in the manufacture of artificial leathers and similar products where a high degree of strength and good embossing properties are desired; a latex foam from which car seat cushions, mattresses, and similar products can be manufactured directly; and a wire which has a rubber insulation of such unusual high quality and uniformity that it permits a reduction in the over-all diameter. Substantial quantities of latex are also being introduced into industries which were unable to use dry rubber in their manufacturing processes.

Motor Vehicles

General Motors Research Corporation

About 1909 C. F. Kettering visualized a research organization for the purpose of initiating improvements upon which he felt the future of the automobile industry depended. The Dayton Engineering Laboratories Company was established to carry out the program Kettering had conceived. The company hoped to license its subsequent developments to the various car or accessory manufacturers and in this way to obtain funds for future investigations. Realizing that research and production, if housed under the same roof, might prove to be unfortunate rivals for the company's time and effort, the men in the enterprise decided not to enter immediately the manufacturing field.

The first project of the newly organized company was a battery ignition system, which found favor in the eyes of several manufacturers. Inasmuch as the system consisted chiefly of a coil and several small parts or contacts, the Kellogg Switchboard and Supply Company of Chicago undertook to manufacture the unit, and a license arrangement was agreed upon. In this way funds were obtained for further research, and the company could continue on its original purpose.

In 1912, the company offered the self-starter to the automobile manufacturers. A problem immediately presented itself, however. Because of certain features in the construction of this new unit, it could not be readily produced by an outside company. The laboratories, therefore, undertook the assembly of the starter, purchasing the parts from different manufacturers. In this way the company became a manufacturing concern, still devoting, however, part of its energies to fundamental research, out of which, incidentally, came the Delco farm lighting unit in 1914. After an unsuccessful attempt to have an outside company manufacture the unit, the farm lighting division of Delco was organized to take over the production.

At the time the United States entered the First World War, several of the manufacturers of accessories found it necessary to combine in order to stabilize the accessory business. Consequently, the United Motors Corporation was organized, with Alfred P. Sloan, Jr., as president. This organization later purchased by General Motors included Delco, Remy, New Departure, Hyatt, and Perlam Rim.

In 1917 Kettering, realizing that facilities for general automotive research were limited because of the requirements of production, returned again to the idea of a laboratory for fundamental research and organized the Dayton Research Laboratories Company, with Mr. F. O. Clements as director. The newly organized company focused its energies chiefly on the problem of detonation.

During the early months of the country's participation in the First World War, the Government often had occasion to ask the assistance of the organization in the solution of war problems, among them the gyroscopic control of aerial torpedoes. Later the company found difficulty in obtaining raw materials because of the enforcement of the priority list. In order to overcome this handicap, the company became associated with the Dayton Metal Products Company as its research division, but engaged also in research and production work for the Dayton Wright Airplane Company.

At the end of the war, the company again turned its attention to automotive research, concentrating its efforts on ethyl gasoline, combustion studies, and air-cooling problems. General Motors at this time became interested in these projects and purchased the Dayton Metal Products Company and also the Dayton Wright Airplane Co.

In 1920 the General Motors Research Corporation was established at Moraine City, Ohio, with C. F. Kettering as president and F. O. Clements as technical director. This step marks the beginning of the present period of the research laboratories. In the summer of 1925 the Research Corporation transferred its laboratories to Detroit to be nearer the manufacturing divisions of the company, and its name was changed to General Motors Corporation, Research Laboratories. At this time it was merged with the General Motors

Research Department which had been established by Arthur D. Little, Inc., at Detroit in 1911. The laboratories quickly outgrew the quarters assigned to them, and in 1929 were moved into a new building. On January 1, 1938, research was given the status of a full division and is now the Research Laboratories Division, General Motors Corporation, with C. F. Kettering as general manager.

The research workers in General Motors have contributed to every product or study in which the corporation has had an interest. The wide variety of the problems engaging the attention of the staff and the importance of its work to the automotive industry are clearly indicated by such accomplishments as lacquer finishes, ethyl gasoline, powdered metal oilless bearings, two-cycle Diesel engines, static and dynamic balancing machines, quick process malleable iron, two-way hydraulic shock absorbers, hypoid gear lubricants, and rubber bushings.

Chrysler Corporation

In 1924, when the public first viewed a Chrysler automobile, the company's engineering research facilities consisted of a 3-room laboratory in a small wooden building. Today the engineering and research division with a staff of 55 technical workers and more than 1,000 other employees is housed in new, fully equipped laboratories, in which on an average day 1,500 research tests and projects are in progress, while on some days the number reaches 2,500. Each project has a carefully defined objective, a detailed budget, and a deadline for its completion. These limitations are altered only when the research is clearly proceeding toward a desired end, for Chrysler engineering and research must "pay off eventually in a better car or a lower cost of manufacture."

The company's engineering and research is subdivided roughly into three divisions, (1) fundamental research, which seeks new ways of designing a car and its parts, (2) the analysis, testing, and control of materials, parts, and processes involved in the production of the next model, (3) the testing of the completed car and the comparison of the results with those from similar tests upon the cars of competitors.

Work in the first category is concerned with projects that point toward the automobile of the future. Engineers test scale models in a wind tunnel in order to determine the changes necessary in design to reduce the resistance of an automobile to both head winds and cross winds. From such studies the engineer learned that a "typical sedan in 1932 could go backward with about half the resistance with which it could go forward."

Physicists study the interplay of scores of vibrations of varying intensities, durations, and wavelengths in order that engineers may be aided in designing the complementary dampening equipment to this vibration and in properly placing the dampening equipment relative to the center of gravity. Chemists and metallurgists seek new alloys, synthetic rubbers, and plastics that will better meet the loads and stand the speeds of today's high-compression motors.

For years the physiology of the automobile driver has engaged the attention of the company's research workers in order that they may better understand the effects of noise and vibrations on the human system.

The second type of research in the company's laboratories consists of subjecting to rigorous tests every part of the automobile and every material from which those parts are constructed. In the laboratory where routine ferrous tests are made, for example, a single bench is allotted to each of the basic elements in the composition of steel, so that once a specimen piece has been subjected to the various tests its content of carbon and magnesium and copper is accurately known. From these exhaustive tests and analyses of parts and materials, the company is able to write specifications for better materials, new materials, and new parts. The company's laboratories in a sense, therefore, serve a host of industries that supply both the automotive industry and the general public.

Elaborate facilities are provided for the third type of research—that of testing the finished car and comparing it with the cars of other manufacturers. A variety of machines reproduce in the laboratory all the road conditions that a driver could possibly encounter. In fact these conditions can be greatly exaggerated, yet the means of measuring the effects upon the car can be far more accurate and detailed than any that can be established for an actual test on the road.

In the dynamometer building, tests can be run in a completely dehumidified room with the temperature at 45° F. below zero, or in a room where the temperature is far above human tolerance. Nevertheless a final check upon the results obtained in the laboratory is secured by sending fleets of cars to operate in every part of the country under a variety of road conditions.

By its application of science and scientific methods, by its painstaking records of tests and analyses, the company duplicates in a short time years of trial and error effort; and, so far as human planning and foresight can insure it, "seeks to determine its own technological destiny."

Metals

American Brass Company

The American Brass Company included among its member companies the Coe Brass Manufacturing Company of Torrington, Conn. This fact is of importance in a survey of the development of research because William H. Bassett became chemist of the Coe Manufacturing Company in 1902. During that year and in the ones immediately following, while he was chief chemist and metallurgist of the American Brass Company, Bassett initiated a broad program of research which was to have great influence upon the entire copper and brass industry. The program was, in reality, a gradual outgrowth of work demanded by the problems of the industry; for instance, the production of electrolytic copper had resulted in adequate volume but not in the quality necessary for the production of good wrought copper and wrought copper alloys. By cooperating closely with the most able copper metallurgists and refiners of those early days, Bassett succeeded in securing electrolytic copper with properties which were equal to those of the Lake copper that previously had been the standard of the industry.

Such cooperation was not confined to those in the copper refining industry, but was extended to the men in the brass casting shop and brass mill where "rule-of-thumb" methods were in control. In a relatively few months, standard methods of chemical analysis of copper and its alloys had been developed and put into practice throughout the mills of the American Brass Company. Exact chemical ranges of composition of alloys were decided upon, and from that time each alloy was cast to specifications, not only as to copper content but also as to allowable amounts of impurities.

From the multiplicity of problems facing the copper industry one of the first that Bassett selected for study was that of the logical determination and arrangement of data on the properties of copper and copper alloys after cold rolling and after heat treatment or annealing. Charts were prepared showing graphically the tensile strength, elongation, electrical conductivity, hardness, and grain size of many brass, bronze, and nickel alloys. This study, made more instructive by means of photomicrographs, was the first instance in America of the use of the microscope in the examination of the structure of copper and its alloys. With the assistance of Mr. F. G. Smith and Mr. J. C. Bradley, he revealed by methods of polishing and etching the relation of grain size to annealing temperature.

The research department (as such) did not grow rapidly. It gave most of its attention to improving manufacturing methods, yet each of the trained men in the department was expected to give a portion of his time and thought to the solution of research projects.

In 1926 the company's research program was broadened to include a large number of studies in the resistance of alloys to corrosion and the development of new alloy materials. Today its research continues under the direction of H. C. Jennison and J. R. Freeman, Jr.

American Rolling Mill Company

Since its inception the American Rolling Mill Company has given first place to research. Such emphasis was essential, for the company started as a very small concern in 1900, the year that much of the steel industry was consolidated into the largest commercial corporation the world had yet known. The officials of the American Rolling Mill Company felt that if the company were to survive it must enlist the forces of research. Their early and continuing faith in industrial research has been justified, and today the company is the world's largest manufacturer of special-analysis iron and steel sheets.

The company's research can be divided into two parts: one, the study of chemical and metallurgical problems to produce sheets for exacting uses such as drawing, spinning, and the making of alloyed metals; the other, a study and development of mechanical and productive processes to better the product, increase the output, and lower the cost.

Chemical and metallurgical research at the American Rolling Mill Company began when a 25-ton furnace was set aside for experiments in making electrical steel of the uniformity, low hysteresis, and high permeability needed by such concerns as the Westinghouse Company. The relentless toll of rust demanded attention, and experiments were conducted in 1906 to make pure iron in an open hearth furnace, with the result that the company's ingot iron was placed on the market. It won the prize award at the San Francisco Exposition in 1915 for rust resistance, welding, magnetic, and enameling properties. The growing need for stronger lightweight sheets for railroad cars, busses, and products of a similar kind led to intensive research which resulted in the production of the high tensile sheets which are today serving this market with definite advantages.

Closely associated with iron and steel production are the various methods for coating sheets of iron and steel. Recent research has produced galvanized sheets that can be painted immediately without weathering and a galvanized coating that will not peel in forming or spinning. As a result the cost of hand dipping is saved on all sorts of galvanized products.

The invention by John B. Tytus in 1924 of the continuous process for rolling sheets is perhaps the American Rolling Mill Company's greatest contribution to the iron and steel industry. Mills built and equipped for this process by the leading steel companies, under license, have made possible an increase in the use of iron and steel sheets that could not have taken place with hand mill operation.

American Smelting and Refining Company

Early in 1924 the proposal to establish a research department in the American Smelting and Refining Company was given serious consideration. The suggestion was occasioned by the feeling among the officials that systematic research would materially assist the company in maintaining its position in the rapidly advancing nonferrous metallurgical field.

It was believed that the needs of the company could best be served by a staff composed of highly trained scientists, together with men in the plant who had shown a natural aptitude for research. The activities of the staff would be directed toward the investigation, study, and development of established processes, as well as new ones. This staff, together with its facilities, would also be available for technical advice and service to the various plants and, by keeping in touch with scientific progress in other industries, would provide a clearing house for information of interest to the company.

Largely through the efforts of F. H. Brownell, H. A. Prosser, and W. H. Peirce, a laboratory was established in 1925 at the company's plant in Perth Amboy, N. J., under the supervision of Peirce, with C. A. Rose as director. It had a staff of six technical men. A western division was set up in 1926 at Salt Lake City for the purpose of conducting research on smelting and related problems. During the difficult years of the early 1930's, some curtailment in operations was necessary. However, as a result of the active interest of some officials within the company, research was continued and the laboratory was further expanded by a section devoted to physical metallurgy.

United States Steel Corporation

Since the days of Durfee, Ward, and Phipps, applied science has been a factor in the development of the steel industry. The early efforts at research were frugal and inadequate, yet they continually uncovered new facts and paved the way for more fundamental studies.

When the United States Steel Corporation was organized, in 1900, all of the constituent companies had laboratories in which more or less systematic investigations had been carried on for some years. In 1891, for example, W. R. Walker hired Dr. Albert Sauveur to begin the microscopical study of steel, in the laboratory of the South Works of the Illinois Steel Company. At that time only two other men were exploring this field—Osmond in France; Martens in Germany.[108] Five years later Sauveur's microscopical work was interrupted because of Roentgen's discovery of X-rays, and because "a hurricane in the form of a new president . . . struck the South Works of the Illinois Steel Company, which in its violence carried away the metallographical laboratory and its occupants." [109]

After the formation of the corporation, research began to take organized form, and research laboratories designated as such were provided in a number of units. At least four of the subsidiary companies had well directed facilities and personnel prior to the year 1915. In addition to the investigations carried on in the laboratories, a much larger amount of work—sometimes sporadic and inconclusive—was going on at nearly every plant. This work was mainly concerned with mechanical developments rather than metallurgical questions, for only within recent years have appropriate experimental and interpretive techniques been developed to the point at which steel making processes could be studied with reasonable hope of success.

In 1928 the United States Steel Corporation, as distinct from its constituent companies, established a central research laboratory under the direction of Dr. John Johnston. Since that date the widespread research and technical activities of the subsidiary companies of the corporation have been carried on in conjunction with the central laboratory, now located at Kearny, N. J. The staff of this laboratory collaborates with men in the plants where many investigations must be carried out because of the impracticability of reproducing on a small scale in the laboratory the actual conditions encountered in the mills.

The corporation now has, under the supervision of a vice president in charge of metallurgy and research, Rufus E. Zimmerman, about 450 men engaged in research. Their efforts are supplemented by the activities of the control laboratories, numbering more than 80 and employing approximately 2,000 chemists, physicists, metallurgists, and engineers.

During the last decade the corporation's research has increased greatly not only in amount, but also in quality and significance. Closer control of the whole sequence of processes involved in making steel has been secured through a study of the fundamental factors affecting the qualities of steel and through the development of better methods of temperature measurement. A study of the rate of transformation of austenite at a series of temperature levels has led to a new method of treatment which imparts to ordinary carbon steel properties hitherto associated only with alloy steels.

Systematic research on the residual stresses in railroad rails has resulted in a process known as Brunorizing, which yields a rail that retains its ductility at low temperatures.

Twelve years of organized, adequately supported investigations have brought a clear recognition of the value of research to the steel industry.

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[108] Sauveur, A. Metallurgical reminiscences. New York, American Institute of Mining and Metallurgical Engineers, 1937, p. 6.

[109] Metallurgical reminiscences, p. 13. See footnote 108.

Pharmaceuticals

Abbott Laboratories

Dr. Wallace C. Abbott began to practice medicine in Chicago in 1886. Troubled by the indefinite and changeable results that he had obtained from the use of unstandardized fluid extracts and tinctures, he began to study the experiments of the Belgian dosimetrist, Burggraeve. The idea of using only the active principle of a drug plant in place of a watery or alcoholic extract appealed to him. Unable to purchase such a product, he began to isolate the pure alkaloids from the crude drugs and to make his own active-principle granules. From his "laboratory" in an annex to the family kitchen, he was soon supplying granules to other physicians in the neighborhood. After the incorporation of the enterprise in 1900 as the Abbott Alkaloidal Company, the manufacture of other types of products was undertaken, and the nucleus of a chemical research staff was formed. Dr. Alfred S. Burdick's association with the company had much to do with the emphasis given to research.

The First World War placed unusual demands upon all the pharmaceutical laboratories of the country, and resulted in an enlargement of research facilities. The Abbott Laboratories continued their expansion after the war and began research aimed at the development of synthetic medicinals to meet definite needs. One result of this study was a new local anesthetic, particularly useful to doctors working on the eye. A research program in the field of hypnotics led to the production of several new compounds.

In 1922 the Abbott Laboratories acquired the Dermatological Research Laboratories in Philadelphia, which had been founded in 1911 on philanthropic grants for the study of psoriasis and have continued to maintain research there under a highly trained staff.

In recent years the company's search for highly potent sources of vitamins A and D has led to the use of livers of the halibut, which, before 1931, were thrown back into the sea as a useless part of the fish.

Eli Lilly and Company

Other companies were also active in the search for new and more reliable medicinal products. The firm now known as Eli Lilly and Company had equipped a laboratory and employed a chemist for assaying and research by the late eighties. From this small begin-

FIGURE 9.—First Laboratory of Parke, Davis and Company, 1873, Detroit, Michigan

ning the research organization has expanded into the present Lilly Research and Control Laboratories, which are equipped for work in the fields of chemistry, botany, pharmacology, physiology, and experimental medicine. The research staff cooperates constantly with original investigators in universities, clinics, and hospitals, particularly in the study of prophylactic and therapeutic agents. The first insulin commercially available in the United States came as a result of the cooperation of the laboratory with research workers in the University of Toronto.

Parke, Davis and Company

In 1862 Samuel P. Duffield, a retail druggist in Detroit, began to make a number of preparations in larger amounts than required for his own use and to sell them to other pharmacists. In 1866 the partnership of Duffield, Parke & Company was formed, later to become Parke, Davis & Company. From the beginning the company was active in the investigation of new drugs, the production of new medicinal substances, and the development of new methods of manufacturing pharmaceutical products. About 1874 a systematic search was begun for unknown or little used plants that might have medicinal value. Representatives of the company explored the northwestern United States, British Columbia, and Mexico; one sent to the Fiji Islands brought back a supply of tonga; another brought from the West Indies other plants which proved to be valuable as drugs. A special representative in 1881 made a trip from the mouth of the Amazon River about 2,500 miles into the interior. As a result of these explorations and the work in the laboratory the company in the early years of its existence introduced 48 new drugs, many of which are still widely used.[110]

In the seventies there were no standards for medicinal products, and drug extracts varied greatly in strength. In 1879 the first standardized medicinal drug product on the market came from this laboratory. It was a preparation of ergot that had been brought to a uniform standard of strength by a chemical assay.[111] Four years of systematic study made it possible for the company to announce a list of 20 "normal liquids" that had been standardized by some form of chemical assay. Although new and better methods of assay were to be discovered, the original standards have in many instances changed very little. In recent years, much research has been devoted to the means of preparing and stabilizing solutions used in hypodermic and intravenous medications.

A separate biological unit was established in 1895, and in 1902 the necessity for more adequate facilities for research led to the construction of a new research laboratory, which is said to be one of the first separate laboratory buildings erected by a commercial organization in this country. Under the direction of Dr. Oliver Kamm, the laboratory has in recent years expanded until now it comprises some 16 divisions, including organic chemistry, biochemistry, bacteriology, pharmacology, physiology, pathology, and pharmacy, each of which is under the supervision of a specialist.

E. R. Squibb & Sons

Dr. Edward R. Squibb was one of the first men to take steps to fill the need for new and better products in the treatment and prevention of disease and in the relief of pain. He founded the firm of E. R. Squibb & Sons and began at once to develop a process for making ether satisfactory for anesthesia. Since that time the company's research has gradually expanded to provide the medical profession with a greater supply of more effective preparations with which to combat disease. In 1938 the company organized the Squibb Institute for Medical Research, which is housed in a new laboratory building in New Brunswick, N. J. The laboratory is devoted to pure science in the medical and biological fields. Research has been organized in four main divisions—experimental medicine, pharmocology, bacteriology and virus diseases, and organic chemistry.[112]

Miscellaneous Industries

American Locomotive Company

In the locomotive industry the principal objective of research has been improvement in locomotive design and construction to give better and more economical motive power. To achieve this end, research in the laboratory has been supplemented by data obtained from actual road performance.

During the decade from 1890 to 1900 the individual companies which were later consolidated into the American Locomotive Company made extensive studies to obtain a satisfactory application of double expansion steam distribution. As a result of this work, seven or eight types of compound locomotives were introduced, among them the Richmond compound, developed by Carl J. Mellin, which is still the American Locomotive Company's standard for compound locomotives.

Soon after the formation of the company in 1901, experiments were carried out on the use of superheated steam, a practice which has now become standard in locomotive operation. For a period of 10 years the company collected a large amount of operating data from the railroads, and from an analysis of these data it was able to evolve tables giving such information as

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[110] Taylor, F. O. Parke, Davis and Co. *Industrial and Engineering Chemistry, 19,* 1205 (October 1927).

[111] Parke, Davis and Co. See footnote 110.

[112] Dedication of Squibb Institute. *Industrial and Engineering Chemistry (News Ed.), 16,* 564 (October 20, 1938)

locomotive tractive power, hauling capacity, and boiler capacity. These tables became the textbook for locomotive design and locomotive rating for many years.

The company has built 20 experimental locomotives for the most part in cooperation with railroads interested in developing better motive power units. Through plant research the company has produced high grade forgings for locomotive parts and high grade iron castings for general use. It has developed and built the only welded locomotive boiler, and is now devoting considerable attention to fusion welding, both in its application to locomotive construction and in general fabrication work.

Armour and Company

The meat-packing industry was an old one before research came to play any part in it. Phillip Danforth Armour, the founder of Armour & Company, admitted freely that he knew nothing of scientific theory or chemical processes, but he nevertheless encouraged the efforts of his staff to improve operations by scientific methods. A loosely bound organization of scientifically minded men contributed new ideas to the industry long before even a trained chemist was added to the staff.

Previous to 1875, slaughtering operations were conducted only in winter, and the main carcass, which could be sold fresh in winter or barreled in brine or salt for summer use, was the only part of the animal considered worth saving. In spite of ridicule from his contemporaries and associates, Armour, in 1876, had Joseph Nicholson, an early packing house architect, build the first refrigerated meat warehouse in the world.

Before chemistry came to play a part in the meat-packing industry, individuals outside the industry had begun to prosper by salvaging parts of the carcass that had always been discarded as waste. Blood and tankage were among the first waste products to be utilized. For years they had been discarded in the south branch of the Chicago River which, because of the evolution of the gases of fermentation and decomposition, came to be known as "Bubbly Creek." In 1880 animal fats were used to produce oleomargarine commercially, and 2 years later the shin and thigh bones of cattle were dried and used for such articles as buttons and combs. Extract of beef was first produced in 1885.

Armour, observing the marked success of the concerns which bought up the packers' waste products or hauled them for the taking from the dumps, decided to expand his business to include the salvaging of waste. In 1884, his purchase of the glue works of Wahl Brothers formed the nucleus of the present auxiliary plant for utilizing byproducts. A year later Armour entered the pharmaceutical business, making at first only pepsin and pancreatin. Another important step was taken when the waste waters from cooking and other operations were saved and evaporated to recover the valuable protein matter used at that time as fertilizer.

Armour's realization that byproducts might hold hidden treasures led to the application of science to the meat-packing industry. The marvels of chemical research at the World's Columbian Exposition at Chicago in 1893 made a deep impression upon Armour and members of his staff, and that year he hired his first chemist, Dr. A. G. Manns, to give assistance on certain pharmaceutical and refining problems. His work was so satisfactory that Armour commissioned him to equip adequate laboratories and hire the necessary staff. The work of the laboratory increased rapidly. Chemists were added to all departments of the company and kept busy upon immediate problems of control and trouble shooting.

About the same time C. H. MacDowell convinced Armour that profits lay in the direction of better utilization of byproducts as fertilizer and was commissioned to start the venture which became the Armour Fertilizer Works.

In 1907 Paul Rudinick, who succeeded Manns in charge of the chemical laboratories, created a separate department under Dr. Frederick Fenger for pharmaceutical research, and one for research in fertilizers under H. C. Moore. Not until 1928, however, was an attempt made to form a separate research organization. At that time W. P. Hemphill, an executive officer of the company, brought research under his jurisdiction, with J. J. Vollertsen, chief control chemist, in immediate charge. The physical equipment for research remained decentralized until E. L. Lalumier, Hemphill's successor, obtained the first appropriation for a separate research laboratory. From 1930 to 1939 both research and development work were handled by the research department under the direction of V. Conquest. In the latter year the development work was placed under a separate head, and the research program expanded.

Swift and Company

In 1871 G. H. Hammond, a Detroit packer, built a partially successful refrigerator car. Five or six years later Gustavus Franklin Swift, by developing a completely successful one, made possible the erection of centralized meat packing plants near livestock markets such as Chicago. By 1877 Swift and Company was shipping dressed beef to a country-wide trade. With its market greatly expanded, the company's operations increased, and steadily mounting tonnages of blood, grease, and bones were discarded as waste or utilized in a haphazard way to make feeds, fertilizers, soaps, and other finished products. Little serious attention, however, was given to the systematic conversion of waste products into valuable byproducts.

In 1892 a small laboratory was established at the Chicago plant of Swift and Company in a building which served simultaneously as a glue and soap factory. Dr. Joslyn was employed as chief chemist. The stated functions of the laboratory were to analyze and standardize the company's products, and to find answers to problems pertaining not only to the manufacture of major products such as meat and lard, but also to the exploitation of byproducts. Since the meat packing industry offered unexplored territory to the scientist, his discoveries were frequent and led quickly to an expansion of the company's activities. New packing plants were built or purchased, and in each new plant there was a laboratory for analytical and control work. Branch laboratories were installed at St. Louis in 1900, Kansas City and St. Joseph in 1905, Fort Worth in 1906, and subsequently in Omaha, East Cambridge, Portland, San Francisco, Los Angeles, St. Paul, Newark, East St. Louis, Edmonton, Toronto, Harrison, and Atlanta.

Much of the research in the laboratories during the early years of their existence was determined by outside factors. Between 1907 and 1910, the problem of acidulation of phosphate rock to render phosphoric acid available for fertilizers which could supplement the animal fertilizers rich in nitrogen was of paramount importance. A little later a process was worked out by which potash could be recovered from kelp. From 1910 to 1912 the research staff was particularly active in developing modern methods of fat and oil hydrogenation, refining, and bleaching.

Until 1920 the research laboratories were attached to divisions such as glue and gelatin, fat and oil, soap and glycerine, bacteriology, and meat. Trouble shooting, technical sales service, utilization of byproducts were the chief activities of the men in the laboratories, and out of a staff of approximately 50 persons, not more than 8 or 10 were doing actual research.

To relieve the inadequacy of accommodations and to provide for expansion, the company built new laboratory facilities in 1929. Two years later W. D. Richardson, who had been chief chemist for 27 years, resigned and R. C. Newton succeeded him. More trained men were employed to work on problems which the smaller staff had been forced to neglect. New divisions were formed, and coordinated with them were 16 outside laboratories and 160 smaller test rooms devoted to the ever increasing task of controlling the processes and products. Approximately 150 trained men are now engaged in this control work.

At the laboratories in Chicago about 60 persons are engaged at least part of the time in fundamental research in many subjects, including physical chemistry, bacteriology, industrial sanitation, nutrition, histology, and pathology. These men also devote time to development work and to consultation and technical sales service.

Babcock and Wilcox Company

Since the early days of its existence Babcock & Wilcox Company has carried on laboratory and research work. Until 1900, studies were conducted at Stevens Institute of Technology, under the guidance of T. B. Stillman, Sr., and D. S. Jacobus. From 1900 to 1910 a small wooden building in Bayonne, N. J., housed 3 to 4 men engaged in laboratory work on fuel, combustion, and water analyses. In 1910 the company established at Bayonne a complete chemical, physical, and metallurgical laboratory, and placed a competent chemist and metallurgist in charge of it. This laboratory continued in operation until 1932, when it was moved to the company's plant at Barberton, Ohio, and consolidated with two other laboratories. Besides this laboratory, the company now maintains a complete metallurgical and physical laboratory at Beaver Falls, Pa., and a third laboratory at Augusta, Ga., especially equipped for refractory research. To complement research work in its own laboratories the company has supported research in technical institutions.

Most of the company's research has naturally been devoted to subjects affecting the construction and operation of boilers, which in 50 years have changed from hand fired cast-iron boilers having a capacity of 3,000 to 4,000 pounds of steam an hour at 160 pounds pressure to completely automatic units fired with pulverized fuel, producing more than 1,000,000 pounds of steam an hour at a pressure of 2,600 pounds. Research on refractories, however, has led the company into the manufacture of firebrick and insulating materials, products which find little use in connection with boilers.

Bausch & Lomb Optical Company

The Bausch and Lomb Optical Company, is said to owe its existence to the imagination of J. J. Bausch in foreseeing the advantages of hard rubber as a material for making spectacle frames.

A chemical laboratory was established by the company in 1899, with John Wood Scott as chemist in charge. The primary purpose of this laboratory was the preparation of chemicals to be sold through the chemical supply division which, at that time, was an active division of the company. Shortly after the laboratory was founded, it was asked to undertake research on lacquers for finishing metal, cements for use in the lens departments, and abrasive materials for use in grinding lenses. Before the end of the year, 1899, Mr. Frank Kolb was engaged to work primarily on such problems. He was soon put in charge of the chemical laboratory and has held that position up to the present time.

The activities of this early chemical laboratory were the special interest of Henry Bausch. As the company grew, the responsibilities of the laboratory naturally increased. It was called on for aid in the early experiments in the making of optical glass, inspired by William Bausch; it undertook research in all kinds of metal plating; and the latest step in its expansion was the addition of the equipment and personnel necessary to handle the company's work in metallurgy.

In 1905 the scientific bureau was established, primarily to perfect optical designs, to carry out such research as might be necessary or appropriate to establish standards of performance, and to devise testing equipment for use in the factory in producing instruments that measured up to the established standards of performance. The man employed to head this department was Dr. G. A. H. Kellner, who had been educated at the Universitites of Jena and Berlin and who had had practical experience in the optical industries of Germany. Attached to his staff were Adolph and Henry Lomb, Jr., and Fred Saegmuller. In 1908 Dr. Kellner engaged the services of W. B. Rayton, and lost the services of the other 3 men mentioned because of the continued growth of the business and the necessity to draft these men for other responsibilities. From this small beginning the department grew until on January 1, 1940, its staff consisted of a total of 39 people, including optical engineers, electrical engineers, and mechanical engineers.

Dr. Kellner's first undertaking was a revision of the line of microscope objectives that were manufactured by the company. At the same time he began a revision of the optical systems employed in a group of engineering instruments which the company had begun to manufacture after its absorption of the business of the George N. Saegmuller Company of Washington in 1905. A new interest, introduced into the company's activities by Saegmuller, was the development of fire-control instruments for the United States Navy—instruments such as gun sights, periscopes, range finders, and miscellaneous telescopes. Prior to this time the Navy had very little equipment of this sort, and the years between 1905 and 1914 were active ones in both the Bureau of Ordnance of the Navy and the scientific bureau of the Bausch & Lomb Optical Company in developing various equipment which was more or less experimental in the study of the whole problem of determining ranges and aiming guns.

The scientific bureau has continued research upon the company's original products—spectacle lenses and frames. In 1912 it began studies in the performance of curved forms of lenses. The general development of the whole field of ophthalmology has perforce led the company into the design and manufacture of elaborate instruments for diagnosis of the pathology of the eyes and for the determination of refractive errors.

As a result of the First World War the company had to supplement its lines of products by a group of laboratory instruments such as spectrometers, refractometers, spectrographs, and colorimeters. Responsibility for developments in this field rested on the scientific bureau. A survey revealed the fact that too many of these instruments were so designed that the operator, instead of being able to concentrate on his main problem, had to devote a large part of his time and ingenuity to keeping the instruments in working order. Until his death in 1926, Dr. Kellner manifested a keen interest in the design of such instruments.

Following Dr. Kellner's death, Dr. Rayton was made head of the bureau, where subsequent developments have added to the original responsibility for optical design, the responsibility for the mechanical design of all optical instruments manufactured by the company. By continuous research involving the properties of materials and the suitability of designs, this department has, through improved instruments, advanced the work of both the research and routine laboratories of the country.

A third research group maintained by the Bausch & Lomb Optical Company is concerned with the problems of manufacturing optical glass. This group obtains assistance from the chemical laboratory and from the scientific bureau, the former doing analytical work and the latter investigating the quality of glass as regards its effect on the performance of lenses and instruments. The glass research group proper is concerned with the problems of melting, annealing, and inspecting optical glass. Work in this field was begun shortly before the outbreak of the First World War. The conditions that resulted from the war made it absolutely necessary that the company solve the problem of manufacturing optical glass. The emergency was so serious that the Geophysical Laboratory of the Carnegie Institution of Washington assigned several members of its staff to duty at the glass plant of the Bausch & Lomb Optical Company, and, as a consequence, the progress made in the years 1917 and 1918 was many times greater than it would otherwise have been. In spite of the fact, however, that throughout these years very large quantities of usable optical glass were manufactured, the number of kinds made was small, and much remained to be done to reduce the cost of production and to improve the quality of the product. Formulas and techniques required for the production of a wider range of glasses also had to be developed after the war.

As the interests of the company have expanded so, too, have the activities of its research laboratories in which 130 workers are now employed.

Consolidated Edison Company of New York, Incorporated

Public utilities providing electric, gas, or steam service are faced with research problems that are different in many ways from those of manufacturing companies. They do not usually manufacture or sell products and are not directly interested in creating new products. Their function is to provide service at the least possible cost to the public. To a very considerable degree, the plant and facilities of a utility company are composed of more or less complete units purchased from manufacturers. The engineering problems are, therefore, largely those of selecting suitable equipment and assembling it in a way that will give the most effective operation. Only to a limited extent does the company fabricate raw materials.

Many of the items of equipment, however, are such that they cannot be tested thoroughly by the manufacturer. Large steam turbine generating units, electric power cables, large gas manufacturing equipment must be operated under service conditions in order to determine their limitations and possibilities. Therefore, the chief tasks of research workers in the utility industry are the critical examination of problems arising from the operation of equipment and the interpretation of the results of such an examination in ways that will be useful in designing and manufacturing equipment. The utilities rarely make basic designs for such equipment, however, but are continually confronted with the problem of choosing between a number of designs offered by various manufacturers. An intelligent choice requires knowledge of the controlling factors. Occasionally it is necessary for the utility companies, as purchasers of equipment, to make demands that will accelerate progress, but these can be made intelligently only when those calling for the new type of equipment have a sufficiently detailed understanding of the problems involved to know that their solution is practical and economically sound.

Other research arises in connection with the adapting of utility company services to the needs of customers. Most of the activity in this connection is of an engineering or technical nature, but there is a continual sprinkling of problems, such as corrosion of pipes and equipment utilizing gas or steam, which demand the more fundamental approach that can be made only by a research organization.

The Consolidated Edison Company of New York is one of the few utilities in the country that has set up research as a distinct activity. In most companies it is a part of the engineering and operating divisions. The present research organization of this company is an outgrowth of the work of a small group formed in 1922 and charged with the responsibility of handling a variety of technical problems in connection with high voltage electric power cables on the new power transmission system which was then being evolved. An important phase of the early work was the development of new test techniques for use in the investigation of the cables and the making of suitable joint designs. This effort was gradually expanded to include methods for checking new installations of cable and for locating faults when they occurred. Gradually these procedures became more or less routine and were eventually transferred to the company's testing and operating departments.

For 15 years electrical insulation has been an important study in the company's laboratory. Today, attention is directed particularly to the factors influencing the deterioration of electrical insulation and to the establishment of criteria for use by the engineering departments in their selection of cables. Many aspects of this work are so fundamental that a study of them requires men with a knowledge of physical chemistry and physics.

Improved efficiencies in the utilization of fuel have been possible only through the extensive use of new products of the metallurgical industry; consequently work in metallurgy has been of growing importance. Although the materials which are used in the production and fabrication of metals are carefully selected, they must be put into actual service before their essential characteristics can be determined. The company has, therefore, found it very important to have in its research organization trained metallurgists, as only they can obtain the necessary fundamental information. Extensive laboratory studies are frequently required to explain conditions observed in the field.

The personnel of the research organization in the Consolidated Edison Company, totaling about 30, is not large, but the assistance of a large technical service organization and of the engineering departments is available whenever specific projects demand an increased personnel.

Eastman Kodak Company

While still a bank clerk, George Eastman began the research which laid the foundation for the present Eastman Kodak Company. Keenly interested in photography, he was annoyed at having to carry about a dark tent and silver bath whenever he wished to take a picture, and when an article in an English journal suggested to him a possible improvement in the art, he set about "to compose an emulsion that could be coated and dried on a glass plate and retain its properties long enough to be used in the field." His first experiments brought small results, but finally he found a coating of gelatin and silver that had all the necessary photographic qualities.

The thought then came to him that other photographers must also be eager to rid themselves of the cumbersome equipment required for taking pictures.

By June 1879 he was making and marketing plates that were entirely successful, and a month later he got his first patent in England on a process for coating the plates. Experiment after experiment was made to improve both the emulsion and the machine in which the plates were coated. Meanwhile the demand for the product was increasing, and Eastman's fame was spreading. Catastrophe was soon to strike, however. Photographers began to complain that the Eastman plates were dead. Recalling all the stock in the hands of dealers, Eastman began to search for a dependable emulsion. Four hundred and fifty-four attempts at mixing, cooking, and testing brought the same result—a "slight red fog and slight veil." Neither his own formula nor any other would produce a clear plate. After 18 more attempts he obtained an emulsion "free from red fog" but his success was fleeting; the bottle broke, and he lost it all.[113]

Following a brief trip to England, Eastman resumed his experiments in Rochester. Very soon his plates were again "clear and good." The hundreds of unsuccessful experiments and the information obtained during his stay in England had given Eastman the clue to the difficulty, which lay not in his formula or machine but in the gelatin being received from the manufacturers. Thereafter he tested every chemical or ingredient before he purchased a supply.

Although Eastman was not the first person who had had the idea of using some substance other than glass as a base for the emulsion, he now turned his efforts in that direction. In a letter to one of his attorneys, he says:

> I first conceived the process of making Transparent Film by coating a support with a solution of Nitro Cellulose, and then coating it with emulsion and afterwards stripping it off—early in the year 1884, not later than Feb. or Mar.[114]

Innumerable technical and chemical problems arose during the development of this new product, and the first commercial film was not made until March 26, 1885.[115] Far from satisfied with this film, but convinced

Figure 10.—Starting Out in 1880 to Take a Picture

Acme Photo

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[113] Ackerman, Carl W. George Eastman. Boston, New York, Houghton Mifflin Co., 1930, p. 43.

[114] George Eastman, p. 45. See footnote 113.

[115] George Eastman, p. 54. See footnote 113.

that he was on the right track, Eastman decided to obtain the services of a trained chemist. He consulted Professor Samuel Allan Lattimore, head of the Department of Chemistry at the University of Rochester. Dr. Lattimore's assistant was an "ingenious, quick witted fellow" named Henry M. Reichenbach, and sometime in August 1886, Eastman offered him a position in which he was to "devote his time entirely to experiments." Unlike many employers, Eastman was not impatient, and a year later in reporting the results of the experiments to one of his associates in London he says of his chemist

> He knows nothing about photography . . . I told him what was wanted and that it might take a day, a week, a month or a year to get it, or perhaps longer, but that it was a dead sure thing in the end.[116]

Eastman's confidence in research was justified. After trying one thing after another, Reichenbach eventually found what he sought—the formula for a transparent, flexible film, which he patented December 10, 1889. Eastman again wrote to his associate in London, this time offering a bit of advice:

> It will not be long before your concern will need a practical chemist. . . . The best way to do is to make application to the Prof. of Chemistry in some good technical school and have him recommend two or three first class boys. You can interview them and take your choice—If he is any good he will be the most profitable man you can hire.[117]

Research was reducing photography from a complicated process requiring study and practice to a few simple operations which the amateur could easily perform. But there was much to be done, and Eastman sought more chemists. In 1891 he asked Prof. Thomas M. Drown, of the Massachusetts Institute of Technology, to select a young chemist from the graduating class and to have him devote (during the remaining months of his training) some attention to photographic chemistry. Upon Reichenbach's dismissal, Eastman sought recommendations for a young chemist from professors at Johns Hopkins, Columbia, and Cornell. At the same time he employed Dr. Leonard Paget to continue the company's research work in New York City.

When Eastman built new buildings in 1893 at Kodak Park, he provided space for a new experimental laboratory, to which he called attention in a *Prospectus for Kodak, Limited*, as follows:

> Special chemical and mechanical departments with a staff of skilled hands are maintained for *experimental* purposes in order to keep in advance of all demands for improvements in every branch of photography.[118]

In 1910 the laboratory was enlarged, and 2 years later a building at Kodak Park was completely remodelled to provide adequate facilities for all kinds of experiments—chemical and physical. The company's research now included not only problems of immediate interest in the manufacture of photographic supplies, but also questions of scientific nature that might have an application in the photographic industry. A man of unusual training and experience was needed to organize and direct the work of the laboratory, and while abroad in 1912, Eastman found such a man in Dr. C. E. Kenneth Mees, one of the managing directors of a small firm of photographic manufacturers in England. He was a chemist, a physicist, also a practical manufacturer of color-sensitive dry plates and color screens used in photography. Mees came to America and has been in charge of the Eastman laboratory ever since. His firm, Wratten & Wainwright, Ltd., was incorporated in the English company, Kodak Ltd.

From the early days of the laboratory, organic chemicals used in the company's research were prepared in the organic chemistry laboratory, and a feature of the laboratory particularly interesting to foreign visitors was the equipment which made it possible to try out new processes on a miniature factory scale.[119] When the First World War cut off the supply of synthetic organic chemicals coming from Germany, this experience and equipment proved especially valuable to this country. The laboratory soon became the chief source in the United States for organic chemicals used in research. It can now supply industrial and university laboratories with more than 3,000 such chemicals.[120]

Research has led to a tremendous expansion of the photographic industry, and, in turn, the expansion of the industry has greatly extended the range of problems with which the research laboratory has to deal. Today the work of the Kodak Research Laboratories falls naturally under the three subjects of photography, chemistry, and physics. Under those three main divisions, groups in the laboratory are doing fundamental research as well as development and service work. Some idea of the extent and complexity of the company's research can be gained from the following description of the Chemical Division:

> . . . Each of the main divisions of the laboratory is subdivided into smaller specialist departments dealing with particular subjects. The chemical Division includes the following laboratories: Organic Chemisty, for general organic research, particularly on cellulose and cellulose esters; Photochemistry, for

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[116] George Eastman, p. 57. See footnote 113.

[117] George Eastman, p. 63. See footnote 113.

[118] George Eastman, p. 145. See footnote 113.

[119] Fleming, A. P. M. Industrial research in the United States of America. London, H. M. Stationery Office, 1917, p. 7.

[120] Rochester—the city of varied industries. *Industrial and Engineering Chemistry, (News Ed.), 15*, 287 (July 10, 1937); Mees, C. E. K. Manuscript.

> fundamental research on the theory of photographic sensitivity and development; High Vacuum Chemistry, dealing with vacuum pumps and gages for molecular distillation and vapor-pressure measurements; Electro-chemical Measurements, including Redex potentials of developers, electrometric titration, determination of hydrogen-ion concentration; Colloid Chemistry of Gelatin, Physical Chemistry of Film Support; Research on problems arising from the use of cellulose acetate yarn in textile processes, including a physical testing of yarn and the dyeing properties of textile materials; Micro-analysis; X-ray examination of structure; Photographic emulsions and Sensitizing dyes.[121]

More than 400 workers, over half of whom have university degrees, are now required to carry on the company's extensive research program.

Johns-Manville Company

In the seventies H. W. Johns was experimenting with an oil stove, a teakettle with a flattened spout, and an ordinary clothes wringer to produce a fireproof roofing from saturated wool felt, burlap, manila paper, pitch, and asbestos. His experiments were successful, and for more than 20 years his efforts were devoted largely to the development of commercial products that could be manufactured from asbestos. Looking about in 1899 for a man who would make himself generally useful, Johns hired William Robbins Seigle, then 20 years old. Ten years later, when the H. W. Johns-Manville Company purchased the Indurated Fibre Company at Lockport, N. Y., Seigle joined forces with Prof. C. L. Norton, who had developed a process for making "homogeneous sheets from a combination of asbestos and cement formed together under heavy pressure."

Although not a scientist by training, Seigle believed that if inventors working alone and with little scientific knowledge could occasionally make discoveries that were important for industry, then highly skilled scientists working with adequate facilities could make many more such discoveries. In 1916 he organized with Professor Norton the Norton Laboratories, Inc., at Lockport, N. Y., and in 1917 he set up the W. R. Seigle Laboratories in the garage of his home in Mamaroneck. When the garage became too small for his research activities, he moved the laboratory to Bridgeport, Conn., and incorporated the enterprise as the Fibrefraks Laboratories. Although Seigle carried on the research as a personal activity, Johns-Manville profited by it in many ways. Asbesto-cement pipe, for example, was made possible very largely as a result of knowledge obtained in Seigle's laboratory.

In time Johns-Manville purchased the Fibrefraks Laboratories and centered all the company's research at the Manville factory in New Jersey, with Mr. Seigle as director. Under his supervision the research work expanded until the laboratories reached their present size employing more than 125 trained workers, headed by a skilled staff of research engineers. Facilities have been provided in individual laboratories, such as the McMillan Thermal Insulation Laboratory and the Acoustical Laboratory, for special study of each class of materials made by the company. As a result, new materials are developed, existing products are improved, and technical service is given to customers and to the company's manufacturing and sales organizations. Only through research do the company's executives feel that they can be prepared for the future.

National Lead Company—Titanium Division

About 1870 a young French chemist, Dr. A. J. Rossi, came to America and was engaged in a blast furnace operation at Boonton, N. J., where titaniferous ores were being successfully smelted into pig iron. During this experience he became interested in the occurrence of titanium in iron ores.

Mr. James McNaughton, who controlled the large acreage in the Adirondack Mountains where the McIntyre Iron Company had operated a blast furnace for the reduction of titanium-bearing ores, was aware not only of the richness and extent of the titaniferous ore deposits available there, but also of the doubt of blast furnace operators regarding the possibilities of the use of such ore in furnace practice. Confident that effective utilization of the deposits could be made, he secured the services of Rossi, the only person in the country at that time who had any knowledge of the practical smelting of titaniferous ores. About 1890, with Rossi and several friends, McNaughton organized a syndicate and erected a very small blast furnace in Buffalo, N. Y., where titaniferous ores were smelted in various proportions. Rossi secured patents on the processes of smelting such ores and also on the manufacture of various titanium alloys.

In 1908 Rossi separated an impure titanium oxide and proved its unusual opacity as a pigment by mixing it with salad oil and applying the combination as paint. He was probably the first to conceive of the use of titanium oxide as white pigment. In 1912 L. E. Bartan joined Rossi in a systematic program of research on the possibilities of titanium for use as pigment. Together they developed a method of separating titanium oxide from rutile and ilmenite. Through further research, they were able to demonstrate the practicability and value of titanium dioxide as a white pigment of unique qualities and outstanding merit, and later, after additional studies, they produced the composite types of titanium pigments.

As a direct outgrowth of their intensive experimental effort, the Titanium Pigment Company was incorporated and a factory built at Niagara Falls to produce

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[121] Research in the Rochester area. *Industrial and Engineering Chemistry* (*News Ed.*), *15*, 336–337 (August 10, 1937).

titanium pigments, but restrictions imposed by the Government upon the use of power during the First World War delayed the commercial production of titanium pigments until 1918. After experiencing a rapid expansion, the Titanium Pigment Company was dissolved in 1936, and the manufacturing interests, property, and stocks were taken over by the National Lead Company—Titanium Division.

Pittsburgh Plate Glass Company

Since its incorporation in 1883 the Pittsburgh Plate Glass Company has maintaned research departments in its three divisions: glass, paint and varnish, and alkali chemical. Most of the company's research has been an outgrowth of plant problems and commercial requirements, although occasionally the solution of problems quite remote from its operations and regular line of products has been undertaken.

Research in the glass division has resulted in such developments as a continuous process for manufacturing plate glass from a large tank instead of intermittent small pots; a continuous method of grinding and polishing plate glass, which replaced the individual plate polishers; improved finishes of glass; glasses of many different compositions for the purpose of meeting specific requirements; improved refractories for furnaces; new and improved methods of laminating glass; new plastics for laminating glass; new safety glass cements; double glazed windows; glass building blocks; colored enameled glasses; and opaque construction glasses.

The laboratory has recently cooperated with the laboratory of the Carbide and Carbon Chemicals Corporation in the development of vinyl plastic, a new plastic used in the manufacture of laminated safety glass.

United Shoe Machinery Company

It was in 1846 that Elias Howe, Jr., inventor of the sewing machine, revolutionized mechanical sewing by putting the eye of the needle in the point. In 1851, John Brooks Nichols, a shoemaker, of Lynn, taking Howe's machine as a model, made a similar machine which sewed the uppers of shoes. The Nichols invention, which may be considered the beginning of what today is research in the shoe industry, was the first important application of machinery to shoemaking.

In 1858, Lyman R. Blake took the second step in the application of mechanical sewing to shoemaking by inventing a machine which sewed the soles of shoes to the uppers. From the time of Nichols and Blake to the present day—a period of 90 years—shoemaking has changed from handcraft to a highly mechanized industry. Of this period, the last four decades have recorded a very large proportion of the major developments in invention and technical progress.

With the founding of the United Shoe Machinery Company in 1899 came the first systematic application of scientific methods to the shoe industry. Conditions, prior to that time, in so far as the development of shoe machinery was concerned, were notably chaotic and unsatisfactory not only for inventors and manufacturers of machinery, but also for their prospective customers—those engaged in the manufacture of shoes.

During the latter part of the century, an increasing number of men had acquired knowledge and skill in the development of machines designed to replace hand work, but there was an almost complete lack of coordination among these inventors. The need for systematic organization and mobilization of effort was one of the fundamental reasons for the founding of the United Shoe Machinery Company.

Over the past 40 years the company's experimental and research activities have led to the development of new production techniques, of improved products, and of more efficient service for the shoe industry. In the field of machine development, the company has contributed essentially and broadly to a rise in labor productivity, to a reduction in production costs, and to a mechanization of hundreds of operations formerly done by hand.

During the last decade, the increase both in the number of research problems in the shoe industry and in their complexity has made it imperative for the research division to develop a program of coordinated effort. In the field of machinery development, for example, it is seldom practical for independent inventors to attempt the mastery of all the knowledge necessary for effective procedure. No matter how resourceful the individual may be, he must have the correlated assistance of the chemist, physicist, metallurgist, test-room specialist, and practical shoemaker.

Every year the suggestion department of the company's research division receives more than 3,000 separate items covering a wide range of subjects pertaining to shoe machinery, manufacturing processes, and allied problems. Before these suggestions become the bases for research projects, the commercial, economic, and patent features of each are carefully analyzed. The division's large volume of data relating to the technological developments of the past furnishes invaluable information which influences the recommendations of research management to executive management.

The United Shoe Machinery Corporation embraces a number of affiliate companies engaged in manufacturing lasts, wood heels, eyelets, tacks and nails, shoe cartons, shoelaces, tanning machinery, chemicals used in the shoe industry, and hand tools. Research for all of these subsidiaries is sponsored by the research division, and the direction of new developments is systematically divided among competent specialists.

Committees are used as an effective means of coordinating research activities with the various operating departments of the business. For example, an operating department committee, consisting of representatives from both the research division and a commercial department, review periodically the details of all developments for that department respecting progress, direction, and cost.

Two other important committees are the shoe machinery program committee, and affiliate companies' program committee which have the responsibility of planning major developments in machines, processes, and products, and of formulating definite long range objectives.

The company has recently enlarged its experimental laboratory and now has more than 600 persons employed in the research division.

Western Precipitation Corporation

In 1906 Frederick Gardner Cottrell, a professor of physical chemistry at the University of California, did the first work of any commercial significance in the field of electrical precipitation—a principle that was discovered by Hohlfeld, at Leipzig, in 1824. After plant tests of Cottrell's precipitator were made at the sulfuric acid works of E. I. du Pont de Nemours in Pinole, Calif., a commercial installation was made in 1907 at the plant of the Selby Lead Smelter to collect the sulfuric acid fumes escaping from the gold and silver parting kettles.

Once the practicability of the process had been demonstrated, Dr. Cottrell and three associates founded the International Precipitation Company to act as a holding company for patents and to operate the world over through engineering organizations in various territorial districts. The Western Precipitation Company was organized to handle the engineering work in the western states. In 1911 the latter acquired its parent company. Not until 1936, however, was the name changed to the Western Precipitation Corporation.

The corporation is a research, development, and engineering enterprise, augmented by a construction department. Although still specializing in the electrical precipitation process, the company is also active in the field of dust and fume control and in the air conditioning of materials. For 30 years Walter A. Schmidt has been its director.

An interesting outgrowth of the International Precipitation Company is the Research Corporation. When the Western Precipitation Company was formed, Cottrell and his associates in the International Precipitation Company offered their patent rights for the eastern territory in the United States to the Smithsonian Institution as an endowment for scientific research. Although the members of the Board of Regents did not deem it wise for the Institution to become direct owner of the patents, they were willing to accept a declaration of trust from the owners of the patents and to operate them in the interests of the Institution and pay over to it any net profits.[122] As a result of this decision, the Research Corporation was organized in 1912 and capitalized by a group of men anxious to further without personal profit Dr. Cottrell's objects, which, as stated in the charter of the corporation, are

> . . . to provide means for the advancement and extension of technical and scientific investigation, research, and experimentation by contributing the net earnings of the corporation, over and above such sum or sums as may be reserved or retained and held as an endowment fund or working capital, . . . to the Smithsonian Institution, and such other scientific and educational institutions and societies as the Board of Directors may from time to time select in order to enable such institutions and societies to conduct such investigations, research, and experimentation.

Dr. Cottrell hoped particularly that the Research Corporation would prove to be a means of getting closer and more effective cooperation between universities and technical schools and industrial plants, yet at the same time keeping the academic institutions or the members of their faculties from becoming involved in business details. The Research Corporation, he believed, would achieve this cooperation by being in a position to develop useful and patentable inventions evolved by men in academic positions in connection with their regular work—inventions which would otherwise be unavailable to the public because of the disinclination of the owners either to undertake the necessary development work or to place their control in the hands of a private interest. The corporation could study the situation and arrange licenses under fair terms so that individual manufacturers would be justified in undertaking the development of the inventions. At the same time it would be accumulating funds from royalties that could be used for further investigations.[123]

Research Institutes

Battelle Memorial Institute

By the will of Gordon Battelle, an industrialist of Columbus, Ohio, the founding of Battelle Memorial Institute was made possible. In the course of his industrial career, which was closely connected with the metallurgical and fuels industries, Battelle came to the conclusion that the furtherance of research in industry would contribute largely to the public welfare, and that a nonprofit research institute, sufficiently financed to insure independence and continuity of

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[122] Cottrell, F. G. The research corporation. *Industrial and Engineering Chemistry*, 4, 864 (December 1912).

[123] The research corporation, p. 865. See footnote 122.

operation, would be in a position to encourage the use of research as a means of industrial progress. His will established a self-perpetuating board of trustees to formulate general policies and to administer the endowments. A director, responsible to the board, was to be in immediate charge of the institute's activities.

The nucleus of a technical staff was assembled, and the first building was ready for occupancy in the summer of 1929. The staff grew as the volume of work increased, until at the end of 1939 it numbered over 200 persons of whom 125 were technically trained. Office and laboratory space has expanded correspondingly, and in 1937 a new building made it possible to establish a complete experimental foundry.

This growth has been in accord with the policy by which the services of the organization have been made available to industry. Endowment income has been utilized to provide physical plant and capital equipment, to finance a considerable body of fundamental research, to publish the resulting knowledge, and to engage in a program of research education. The large and growing bulk of research, however, has been done under a sponsorship plan by which the out-of-pocket cost has been borne by industry, including single companies or groups of companies, associations, and individuals. All results of such work have become the property of the sponsor, including data and patents on new or improved processes and products. In some cases such work may be held in confidence, while in others the results become available for publication.

Because of the desire to maintain a permanent and closely integrated research staff, it has been the policy of the institute to confine its efforts to certain defined fields of research. These are metallurgy, chemistry, fuels, ceramics, applied physics, and electrochemistry. The greater part of the sponsored work has been done for the metal, ceramic, fuel, and chemical industries, but other industries with problems in the special fields noted have accounted for an important fraction. Each year appointments of research associates are given to qualified graduates of accredited universities and colleges who have demonstrated marked aptitude for scientific research.

Mellon Institute

In the early years of this century Dr. Robert Kennedy Duncan was seeking a means by which universities and technical schools could be brought into closer cooperation with industry. He recognized the need for a greater supply of men trained to do industrial research and for a more widespread and direct application of science on the part of small industries, to the end that the public at large might profit.

The plan, known as the Industrial Fellowship System, apparently crystallized in Duncan's mind in 1906 after he had previously spent much time inspecting the factories, laboratories, and universities of various European countries, where he had become impressed with the spirit of cooperation which existed between industry and institutions of learning, to the advantage of both. The contrast with American methods at this time convinced him that some effort should be made to provide for a greater application of science in this country.

Duncan returned from Europe to accept the chair of industrial chemistry at the University of Kansas where in January 1907, he established the first Industrial Fellowship. In his words, this plan gave—

> . . . the manufacturer the privilege of founding in the University a Temporary Industrial Fellowship for the investigation of a specific problem, the solution of which would mutually and materially benefit both the manufacturer himself and the public.[124]

Two years later, quite by chance, Andrew W. Mellon's attention was called indirectly to industrial fellowships through a chemical discovery made in France, which he passed on to the chief chemist of the Gulf Oil Company. The latter reported that the discovery had no practical value and to prove his statement sent Mellon a copy of a book called *The Chemistry of Commerce* by Robert Kennedy Duncan. In the last chapter of that book Mellon read of the plan for industrial fellowships. Both he and his brother, Richard B. Mellon, felt that an institution based upon Duncan's ideas would be a strong force in the direction of improving the standard of living through discoveries and inventions.[125] Consequently they invited Duncan to come to the University of Pittsburgh and establish the system there. He accepted, and in 1911 the first research fellows began their work in temporary quarters. As the result of a substantial gift from Andrew and Richard Mellon in 1915, the system was placed upon a permanent basis as Mellon Institute of Industrial Research. Duncan died in 1914 and was succeeded as Director by Dr. Raymond F. Bacon, the former associate director. He in turn was succeeded by Dr. Edward R. Weidlein, the present director. Although allied cooperatively with the University of Pittsburgh, Mellon Institute has its own building, endowment, and management. It was incorporated in 1927.

Under the Industrial Fellowship System, an individual or a company with a problem to solve may become the donor of a fellowship by contributing to the institute a definite sum of money for a period of not less than 1 year. The funds so donated are used to pay the salary and research expenses of the man or men selected

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[124] Duncan, R. K. Temporary industrial fellowships. *North American Review, 185*, 57 (1907).

[125] Mellon, Andrew. Address for the founders. *Industrial and Engineering Chemistry (News Ed.), 15*, 187 (May 10, 1937).

to carry out the desired investigation, and the institute furnishes such facilities as are necessary for the conduct of the work. The results obtained belong exclusively to the donor, and patents are assigned to him. Where secrecy is necessary, the institute takes every precaution to secure it, but often, after a reasonable time, the knowledge obtained by the various researches is, with the consent of the donor, made generally available through publication.

The soundness of the Industrial Fellowship System and the success it has had are clearly indicated by the statistics of its growth. During the academic year 1911–12, the first year that the system was in operation at the University of Pittsburgh, 23 fellows were engaged. From March 1939 to March 1, 1940, 91 fellowships required the services of 167 fellows and 106 assistants.[126]

A new building, dedicated in 1937, has made it possible for Mellon Institute to expand its activities, and it is interesting to note that in the twenty-seventh annual report of the director, Dr. Weidlein states that fundamental research in technology and pure science is becoming a more important part of the institute's work.

Other Research Institutes

In recent years other research institutes have been founded at several universities and colleges, among them the Institute of Paper Chemistry at Lawrence College in 1929, the Purdue Research Foundation at Purdue University in 1930; the Research Foundation of the Armour Institute of Technology in 1936; and the Ohio State University Research Foundation the same year. The object of all these research foundations is to cooperate with industry in the solution of pure and applied research problems, to the end that the university, the general public, and the industry itself shall be substantially benefited.

Commercial Laboratories

Before the trained chemist, physicist, or metallurgist found much opportunity for regular employment in industry, he frequently served as a consultant on special problems. Members of the faculties at universities and technical schools did most of the consulting work in the nineteenth century, but some courageous individuals, sensing the growing inclination of industrialists to consult specialists, established private laboratories where advice could be purchased and materials could be tested and analyzed.

Two such laboratories were opened in 1836; one in Boston by Dr. Charles T. Jackson, and one in Philadelphia by Dr. James C. Booth.

Charles T. Jackson

Jackson made geological surveys for the States of Maine, Rhode Island, and New Hampshire and for the Federal Government on public lands in the region of Lake Superior. He experimented in his laboratory with the narcotic effects of ether and showed Dr. W. T. G. Morton, a Boston dentist, how to administer it before extracting a patient's tooth. He was the first to make a chemical study of sorghum and to call attention to the vast economic possibilities of cottonseed. His laboratory offered unusual opportunities for a varied experience in the practical applications of chemistry, and it was here that William Channing, Richard Crossley, and Benjamin Silliman, Jr., among others, received some of their training.

James C. Booth

After studying with Wöhler in Hesse-Cassel and with Magnus in Berlin, James C. Booth returned to Philadelphia and opened a student laboratory where men could receive personal instruction in applied chemistry. In 1860 he made an unsuccessful attempt to interest iron manufacturers in a system of control analysis of iron ores.

> . . . He was the first chemist in the United States to use the polariscope for testing sugar; he investigated the production of gelatin; made studies of the ores of iron, nickel, and other metals; served as melter and refiner of the United States Mint at Philadelphia; and acted as consultant and analyst for many chemical industries.[127]

This laboratory, which in 1878 became the firm of Booth, Garrett, and Blair, was the training school for many chemists who later achieved distinction.

Arthur D. Little, Inc.

As a chemist to the Richmond Paper Company at Rumford, R. I., whose mill was the first one in the United States to manufacture wood pulp by the sulfite process invented by B. C. Tilghmann, Dr. Arthur D. Little began his career. In 1886, however, Little formed a partnership with Roger B. Griffin, who had specialized in chemistry under Professor Sabin at the University of Vermont, and they opened a laboratory for carrying on business ". . . as chemical engineers, analytical and consulting chemists, and for doing expert and general laboratory work. . . ." The firm was not started under ideal conditions; it was located in Boston on the sixth floor of a building in which a temperamental elevator, more often than not, made it necessary for clients to walk up. More threatening to their chance for success, however, was the general attitude of suspicion toward chemists. In fact Sir William Crookes had just published an editorial in Chemical News in

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[126] Hamor, W. A. Pure and applied science research at Mellon Institute, 1939–40. *Science, 91*, 407 ff. (1940).

[127] Browne, C. A. The history of chemical education in America between the years 1820–1870. *Journal of Chemical Education, 9*, 714 (April 1932).

which he expressed the conviction that it was no longer possible to hope that a gentleman might secure a livelihood by the practice of analytical chemistry.

Some of the difficulties which faced consulting chemists in those days have been described by Dr. Little:

> . . . The impression prevailed that their reported results were influenced by the interests of their clients. It was charged that they frequently took commissions for recommending products, processes, and equipment, and they were certainly for the most part everywhere underpaid.. . Five dollars was the ruling price for a sanitary analysis of water, and 75¢ for the analysis of a sample of raw sugar. We gave up testing sugar on the day when a composite sample representing 6,000 tons of sugar was brought to us for test at that figure. Clients almost without exception refused to pay charges for consultations and considered that the submission of a $3.00 sample for analysis entitled them to discussion of its use, effects, and merits with no limitation as to time.[128]

The testing of sugar, however, provided most of the work of the commercial chemists in Boston at this time, and, in spite of its previous experience with the 6,000-ton batch, the firm soon obtained the major portion of this work by buying the business of H. Rathgens upon his retirement. Later a few additional clients were secured by buying out another chemist by the name of Austin.

Early in 1893 Griffin suffered a fatal injury in the laboratory, and only after some hesitation and doubt did Little decide to carry on the business alone. He did so for 7 years, and then formed a partnership with William H. Walker.

In 1899 a group of Delaware capitalists sent Dr. Little to Europe with a representative of their group to study the commercial production of "viscose," a compound which had been discovered in 1893 by Cross, Bevan & Beadle, a well-known firm of cellulose chemists in London. Little's report pointed to such important possibilities that a second trip was made to confirm the facts. As a result of this trip, the Cellulose Products Company was organized.

In 1918 Lord Shaugnessy, president of the Canadian Pacific Railway, asked Arthur D. Little, Inc., to organize and carry forward a survey of the natural resources of Canada for the purpose, primarily, of pointing out the industrial opportunities of the country. The work proved to be so important for Canada that it was later transferred to the Council for Scientific and Industrial Research, and thus became an activity of the Canadian Government.

A particularly interesting result followed from an analysis of a German product marketed under the name of "Lactarine." It was brought to the laboratory by William A. Hall, who manufactured in Bellows Falls, Vt., a water paint consisting of a mixture of ground gypsum and glue. He had found that when Lactarine was used in place of glue in his paint, it made the coating insoluble when dry. Lactarine proved to be a mixture of casein and lime, but it could not be imported for less than 30 cents a pound—a figure which, for Hall's purpose, was prohibitive. After proving to Hall that casein could be produced from skimmed milk, the company was commissioned to work out commercial methods for its manufacture. The problem, although not an easy one, was finally solved, and the Casein Company of America was soon doing a business of $2,000 a day. The research had cost Hall a little over $700.

Little's success in giving expert testimony in numerous patent suits also added to his reputation and that of his company. Among the famous cases in which he served as technical advisor were those involving the infringements of the Schultz patents for chrome tanning leather, the Malignani and Howell patents for the evacuation of incandescent electric lamps, and the Waldsrode smokeless powder patent.

A pioneer in the establishment of commercial research laboratories, Little was also a pioneer in arousing American industry to the importance of research and in vitalizing the teaching of chemical engineering. In fact, in spite of the notable achievements of his laboratory, he once wrote that his—

> . . . most significant contributions had been (first) the preaching of the gospel of industrial research during many years when manufacturers had no conception of what research meant and were profoundly skeptical of the value of chemistry to them; (and, second, the) conception of the new method of teaching chemical engineering which, is embodied in the School of Chemical Engineering Practice of the Massachusetts Institute of Technology, and which has been adopted by other institutions.[129]

For years he spoke and wrote in an inimitable style of the possibilities of research, beseeching industrialists to see "the handwriting on the wall."

Miner Laboratories

The Miner Laboratories of Chicago, founded in 1906 as a partnership of A. P. Bryant and Carl S. Miner, but now under the ownership and direction of the latter, has developed from an organization engaged primarily in analyses for industries utilizing the products of midwestern agriculture to one whose major activities are now in the field of industrial research.

Its first significant researches were those conducted during the period 1910 to 1915 in connection with patent litigations. This work led ultimately to the establishment of a fellowship for the study of certain problems connected with the business of manufacturing molded plastic products. Other research followed rapidly, much of it again in connection with patent litigation.

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[128] Little, A. D. Manuscript.

[129] Little. See footnote 128.

A large amount of analytical work for the food industry led to research on ways of improving the marketability of oat hulls, then utilized mainly as a feed material. As a result of this research, the production of furfural was developed on an industrial scale. The publicity that resulted from this development was probably largely responsible for bringing the Miner Laboratories into notice as an agency for industrial research, and since the early 1920's industrial research has increased, until it now constitutes about 80 percent of the activities of the laboratories.

The plan for conducting research most frequently takes the form of fellowships under which one or more chemists devote their efforts to single or multiple problems of a client in the laboratories of the organization. In other cases, however, work is carried on in the laboratory of a client having no research department other than the men working wholly under the supervision of the Miner Laboratories. In still other instances the Miner Laboratories' directing group cooperates with the research departments of clients in the planning and directing of research.

Other Commercial Laboratories

Many other commercial consulting laboratories such as the Barrow-Agee Laboratories, Memphis, Tenn.; Gustavus J. Esselen, Inc., Boston, Mass.; Arthur R. Maas Laboratories, Los Angeles, Calif.; Lucius R. Pitkin, Inc., New York City, N. Y.; Foster D. Snell, Inc., Brooklyn, N. Y.; and Weiss and Downs, New York City, N. Y., are making valuable contributions to industrial progress by conducting important research projects.

Testing Laboratories

Electrical Testing Laboratories

Electrical Testing Laboratories began in 1896 as the Lamp Testing Bureau of the Association of Edison Illuminating Companies. Its initial activity was the inspection and testing of incandescent lamps for about 60 of the light and power companies which were licensees under the Thomas A. Edison patents. Soon, however, the defects in incandescent lamps led to a program of research which has been repeatedly extended as the number or types of lamps has been increased and as electric lighting has grown in importance, until the company's research in the performance of lamps now covers all lamp products made in the United States. Before a standard of candle power was provided by the National Bureau of Standards, Electrical Testing Laboratories maintained one for the electrical industry.

In 1902 the Lamp Testing Bureau was incorporated; in 1904 the name was changed to Electrical Testing Laboratories, and the business expanded to include general electrical testing, chemical testing, mechanical testing, radiometric, and photographic testing. In addition to serving about 30 different industries through general testing work, the company has made tests for engineers and manufacturers; furnished standards of various types to universities, other laboratories, and to manufacturing organizations; certified to the manufacturers of numerous electrical products that their products comply with the specifications of the industry; and carried on research for manufacturers and promoters.

The Meter Code, under which all light and power companies buy meters and metering equipment, was written originally at the Electrical Testing Laboratories under the joint committee of the Association of Edison Illuminating Companies and the National Electric Light Association. After several revisions, this code now constitutes a national standard by which the utility companies and the meter manufacturers determine the quality and operation of watt-hour meters and associated apparatus. The Electrical Testing Laboratories was also intimately connected with a study of electric cables and the establishment of standard specifications for lead-covered, paper-insulated, high-voltage cable. In 1931 the company began exhaustive tests upon electrical appliances. These tests brought to light many defects in the construction of appliances and led indirectly to improvements in them, including better insulation and other safeguards against electrical shock.

At present the company is engaged in research in the field of fluorescent lighting in order to establish proper specifications for operation and design.

Robert W. Hunt and Company

Captain Robert W. Hunt, who superintended the building of the experimental Bessemer convertors at Wyandotte, Mich., and directed the first commercial rolling of steel rails at the Cambria Works in 1867, founded the Robert W. Hunt & Company laboratory in 1888. It was the result primarily of his conviction of the value of inspections and tests to both manufacturer and purchaser and of his belief that the testing could be done more efficiently and economically by a company of impartial engineers organized to represent many purchasers.

At first the work of the laboratory was confined principally to the inspection of rail steel, but was later expanded to include tests of other railway materials and equipment. As cement and steel came to be used in the building industries, the laboratory's staff and equipment were increased to cover the inspection and tests of the new materials. Gradually branch laboratories and offices were established in many of the large cities in the United States and in some European countries.

Although the laboratory has continued to be one primarily for inspection and testing purposes, its chemical, metallurgical, X-ray, photomicrographic and physical testing laboratories are equipped and staffed for some research.

Pittsburgh Testing Laboratory

In 1879 Dr. Gustav Lindenthal, a bridge builder, went to Pittsburgh; with him went William Kent and William F. Zimmerman to act as inspectors of steel on his projects. In the course of their work at the Diamond Iron & Steel Co. they met Alfred E. Hunt, superintendent of the open hearth plant, and George H. Clapp, the plant chemist. Kent and Zimmerman organized the Pittsburgh Testing Laboratory in 1881; Hunt and Clapp joined forces with them later and in 1887 bought them out.

One of the outstanding achievements of the Pittsburgh Testing Laboratory was the proof in 1888 that the Hall process would produce aluminum on a commercial scale. For several years the laboratory exercised control over the production of aluminum by the Pittsburgh Reduction Company.

The testing of portland cement was also a pioneer activity of the laboratory, for which, at one time, the company had branch laboratories in many of the large cement mills in the country. Although the company still tests a great deal of cement, the branch laboratories have long since been taken over by the mills themselves.

The laboratory inspected the steel for such structures as Brooklyn Bridge, the bridge over the Firth of Forth in Scotland, and International Bridge over the Niagara River at Niagara Falls.

In the sense that research frequently involves a succession of suitable tests, each one depending upon an analysis of the results of preceding tests, the Pittsburgh Testing Laboratory, as well as other testing laboratories, can be said to do some industrial research.

The United States Testing Company, Inc.

The United States Testing Company, Inc., developed from the needs of a particular industry. Prior to 1872 the raw silk used in the manufacture of merchandise in the United States came principally from China, Italy, and France. Conditioning houses in France and Italy determined the size, quality, gum and water content of much of the raw silk that was sent to the United States, but no facilities existed for getting similar information regarding the raw silk from China. As a step toward a remedy for this situation, The Silk Association of America, Inc., was formed in 1872. Its first report contained a recommendation that a conditioning house be established in New York City.

In September 1880, Messrs. Poidebard and Muzard issued a printed announcement to the silk trade that they were establishing the New York Silk and Wool Conditioning Works. After a difficult career financially, the company, whose name had meanwhile been changed to the New York Silk Conditioning Works, was merged in 1909 with the United States Silk Conditioning Company, which had been incorporated in 1907. After D. E. Douty, of the National Bureau of Standards, became general manager in 1913, the company's activities were so greatly extended that the original name no longer accurately indicated the work of the company and, in 1920, it was changed to the United States Testing Company, Inc.

With the hiring of a chemist in 1911, the directors of the company initiated the research which is now conducted on problems relating to the textile industry and to the designing, developing, and manufacturing of standard instruments and apparatus. In 1928 the company developed tints which were fugitive and would eliminate the then prevalent fabric defects due to the use of unsuitable dyes. Continued research has since developed a greater range of shades and at the same time produced tints suitable for rayon and acetates, spun viscose, wool, and silk.

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SECTION II

2. RESEARCH—A RESOURCE TO SMALL COMPANIES

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ABSTRACT

This report on research in the small company is based on a statistical study of 50 companies located in 6 industrial centers of New England. They range in size from 33 wage earners to 1,500, and in total assets from $150,000 to $2,500,000. In addition to this statistical survey a considerable number of other small companies was studied to give a broader basis for the generalizations of the report.

The outstanding feature of the small company is its technical uniqueness—in respect to a process, a product, a service to industry, or a selected market.

Research, which for the small company is "organized fact-finding," is carried on by the company itself in varying degrees of complexity of organization, and is besides the product of collaboration with research agencies, technical institutions, suppliers, equipment manufacturers, customers, and even competitors. In the small company it is usually very individualistic, relying on the inspiration of one or a few executives.

There is no apparent relation between the size of the company and the amount of research carried on as evidenced by the number of research workers, kind of research organization, or number of fields of research. The determining factor seems rather to be the kind of process or product.

The small company can be self-sufficient in the matter of immediate product or process developments, but for research which is concerned with the long-range type of development it needs the help of outside agencies. This includes the use of private research laboratories, technical institutions, and the buying or licensing of new developments from individuals or other companies. Such use, however, is markedly intermittent.

Additional resources in research for the small company are in the participations by their personnel in the activities of professional societies, the informal exchange of information among staff and clients and suppliers, and especially current technical literature.

Place of Research in Small Enterprises

A striking feature that marks the place of many a small company and explains its existence as a vital factor in our industrial economy is its technical uniqueness. Through the initiative of an individual or through the force of circumstances these small companies create a unique position for themselves by providing services or products that are too specialized for larger corporations to supply profitably. As an extreme example, we have the very small concerns operated by tradesmen or craftsmen whose claim to uniqueness is largely a personal service to a particular clientele in the community. There are also those innumerable proprietors of small businesses who cater to the needs of a locality and who manufacture with a certain amount of ingenuity products which for the most part are in common use. Again, we have the inventor type who has succeeded in building a small business around some technical specialty for which there is but a limited demand.

The more consequential small company for which research begins to be a factor falls largely into the following categories. It may be founded upon some specialized branch of technology, for example the development and manufacture of a special type of gas engine for use in outboard motors. It may cater in a technical way to a selected market, as does the manufacturer of sporting goods, such as fishing rods and flies. It may offer a unique technical product to industry, as for instance some small suppliers to the automotive industry, such as the makers of windshield wipers. Or it may offer a unique engineering service to industry, as, for example, do production die makers.

To obtain a measure of the extent to which research proves to be a resource to the small company, a limited though representative sample of 50 such companies has been examined. In addition to these 50, on which the statistical study in this report is based, a considerable number of others has been studied to give greater validity to the generalizations drawn. Outstanding concerns were selected for study in 6 industrial centers in New England. This is not, then, a typical sample of the small company, for the purpose is not to present a cross section of the industry but rather to present the clearest examples of the extent to which research has proved of benefit to the small company. For this purpose, obviously, companies of little technical accomplishment would add little to our knowledge and so they have been neglected in order to concentrate attention on more successful research methods. But in the latter category as much diversity as possible was achieved in location, type, and size.

The 50 companies of the sample range in size from 33 wage earners to 1,500. Their total assets, as representative of capital employed in the business, range for the majority from slightly over $150,000 up to $2,500,000, while 7 companies having somewhat larger total assets were included in order to provide a connecting link between the typical sample of small company and those of larger proportion. To provide sufficient diversification, the companies investigated include those that were manufacturers of machine tools, process equipment, control instruments, prime movers, mechanical appliances, metal products, rubber, leather, textiles, foods, drugs, pharmaceutical supplies, and a limited number of consumer goods.

Extent of Research in Small Enterprises

Research for the small company must be viewed on the basis of the definition of Dr. C. F. Hirshfeld, the late director of research for the Detroit Edison Company, "research consists of organized fact-finding."[1] It then becomes a question of the extent to which organized fact finding has been carried by companies within this category. The markedly different circumstances of the field of business, the character of the market, the complexity of technology, and the severity of competition make it difficult to draw specific conclusions. The outstanding fact is that, whatever be the extent of organized fact-finding among small businesses, research in the broadest sense gives to such concerns a resource for rendering a unique technical service to industry or the community whereby they hold their place in competition. These companies draw in turn upon technical institutions, suppliers, equipment manufacturers, customers, and at times competitors, for technical developments to supplement their own activities.

The small enterprise has the option of carrying on whatever sort of research it can afford, of developing its own technique, of training its own technicians and experts, of acquiring new knowledge by hiring trained engineers or by participating in professional-society activities, by paying for the services of consultants or scientists, by financing specific research projects through technical institutions, or by buying outright new technical developments or inventions from individuals or other companies. These options are not, of course, mutually exclusive; a company may use first one and then another as the need arises, or more than one may be utilized simultaneously. In fact, the intermittent and irregular use of such kinds of research is the most striking characteristic of its use by the small company. Research is thus both a direct and indirect resource to the small enterprise; it benefits not only from its findings but also from the contributions it is able to make to others.

The importance of research to the small enterprise is brought out by the fact that 12 of the companies interviewed admit that should they immediately cease all forms of organized fact finding in which they are now engaged, they would be forced out of business within a year, while 17 would be seriously affected by the loss of competitive position that would immediately ensue. Six others acknowledge that after a period of approximately 3 years they would forego all technical uniqueness. On the other hand, 13 companies whose distinctive position rests more in serving a selected or regional market or in acknowledged consumer goodwill recognize that the cessation of research would only inhibit the long-term growth of the company. Only 2 companies went so far as to assert that the technology of their field had become so well developed that any effect would be merely incidental.

Of the competitive forces that impel small companies to undertake research, two are of primary importance. The first is the need to satisfy the specific technical requirements of industrial customers; an example would be the manufacture of machine tools for specialized operations. The second is the necessity the small company faces of meeting technical competition with unique developments of its own, as, for example, in the development of impregnated fabrics in such articles as shoe laces. Of almost equal significance is the expressed desire of small entrepreneurs to excel in a specialized field of technology or to establish themselves in a sector of a market which they are peculiarly qualified to serve. An example of this last would be the manufacture of vitamins and hormones. In a few instances the small company holds the position of pioneer on the frontier of an evolving art, as in the use of cast beryllium copper for molds and dies. In the area of consumer goods, factors of market competition take precedence over technical considerations in determining the character of research activities. In many retail products, for example, the package is likely to be at least as important as the product and the elements of appearance and style are given much attention.

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[1] Davis, H. N., and Davies, C. E. Industrial research by mechanical engineers. This volume, p. 329.

In general it can be observed that the small company creates a unique place for itself by rendering through its research a specialized technical service to larger companies or supplies a distinctive product to a select market. For the most part its research activities are characterized by "organized fact finding" of an immediate and practical sort not necessarily set apart in a functional unit, while those of large companies are of a continuing and more intensive nature, carried on in specially organized departments or laboratories and encompass in certain instances advanced research which the small company can rarely afford.

Character of Research Activities

In fields where the art has become well established with less prospect of consequential technical change, organized fact finding assumes the aspect of those engineering activities essential to the improvement of product or process. In attempting to measure the magnitude of research among small enterprises, the intent was to determine the highest type that was essential for a company to maintain its competitive position. Of course, these companies engage as well in the supplementary technical activities of a lesser order down to those of a routine or practical nature.

The research activities of small companies tend naturally to be individualistic. In 6 instances a genius of the inventor type is the moving spirit in developmental work, under whose direction a few technicians carry on the routine tasks. More frequently, as in 11 companies, research centers in a close group of technically trained operating executives. In 9 other cases a technical staff has been built up, the members of which are individually responsible for specific activities to the line executives, rather than constituting a distinct engineering department.

FIGURE 11.—Laboratory for Developing and Testing Refractories, General Refractories Company, Baltimore, Maryland

Although there is no clear-cut line of demarcation, there is evident a correlation between the size of the company and the kind of unit to which it trusts its research. Separate engineering departments are found in 15 companies of our sample of 50, and these companies employ between 150 and 500 wage earners. Departments which engage in both engineering and research are found in 10 companies which range in size from 200 to 1,500 workers although 3 companies with smaller personnel have similar units. Separate units devoted solely to process engineering appear in 17 companies. These 17 cover a considerable range of size, but the greater number of these units are in fairly large companies.

Facilities for Research

The number of experts, engineers, and technicians employed in research by small companies varies without regard to size. For example, in the group of companies employing about 100, there is 1 concern with 12 experts and technicians and another with 13. The number in this group, however, is more likely to run between 3 and 6. At the other extreme, 1 company employing 1,500 has only 10 experts and another with a personnel of 1,200 has but 15. By contrast still another company employing 1,200 has but 58 in research. The factor which determines the need for research workers is obviously not the size of the plant nor of its business, but its character. In some cases the technical activities are a responsibility delegated to operating executives, shop superintendents, or foremen, while in others separate staffs are set up and their numbers run, as we have seen, from 3 to 58. In 12 companies sales engineers constitute an important part of the technical organization.

Size likewise in no way distinguishes the number of technical fields represented by engineers or experts in the employ of small companies. The technical activities of 11 companies fall wholly into 1 field, while those of 22 companies relate to 2 major fields. Nine companies, in turn, have occasion to delve into 3 such fields, while of the remaining 7, 6 operate in 4 fields. All of these companies are scattered over the whole range of size, and there is no apparent relation between size and the number of fields. Mechanical and electrical engineering, together with metallurgy or chemical engineering, were the technologies most frequently encountered in the study. Of course other fields were represented in specific cases, but the variation in number appeared to depend most on the state of the art in the industry, that is, on the age of its establishment and on the degree of its complexity.

While 14 companies have no specialized facilities for research or experimentation, they carry on such activities to the extent that opportunities in the plant permit. Fifteen companies have laboratories for routine testing, out of which come ideas which are further studied through other means. A model shop is maintained by 6 companies and an experimental unit forms a part of the technical activities of 7 others. Specialized research equipment has been installed by 5 companies, scattered throughout the whole range of size of small companies studied.

The continuity of activity was marked testimony to the dependence of the small enterprise on research. Twenty-nine companies claimed that, having built up an effective technical organization, they could not afford to diminish its activity. It is only the routine members of such units that are allowed to vary. In fact, 8 companies pointed to the steady growth of their technical units. Only among 10 companies where the art was relatively well established did the number of trained engineers vary with the needs of the business. It is notable that, for small companies able to cite figures, research expenditures ranged somewhat above 5 percent of net sales for those having more than 200 factory employees and as much as 8–10 percent for those with fewer wage earners.

In contrast to the organized research of large corporations, individual effort characterizes the technical activities of the small company. For the most part, individuals are given the responsibility for specific technical work and only informally exchange ideas or knowledge with their associates. Thus the technical requirements of 20 companies come more within the area of individual ingenuity and accumulated practical experience. Fifteen of these companies spoke of en-

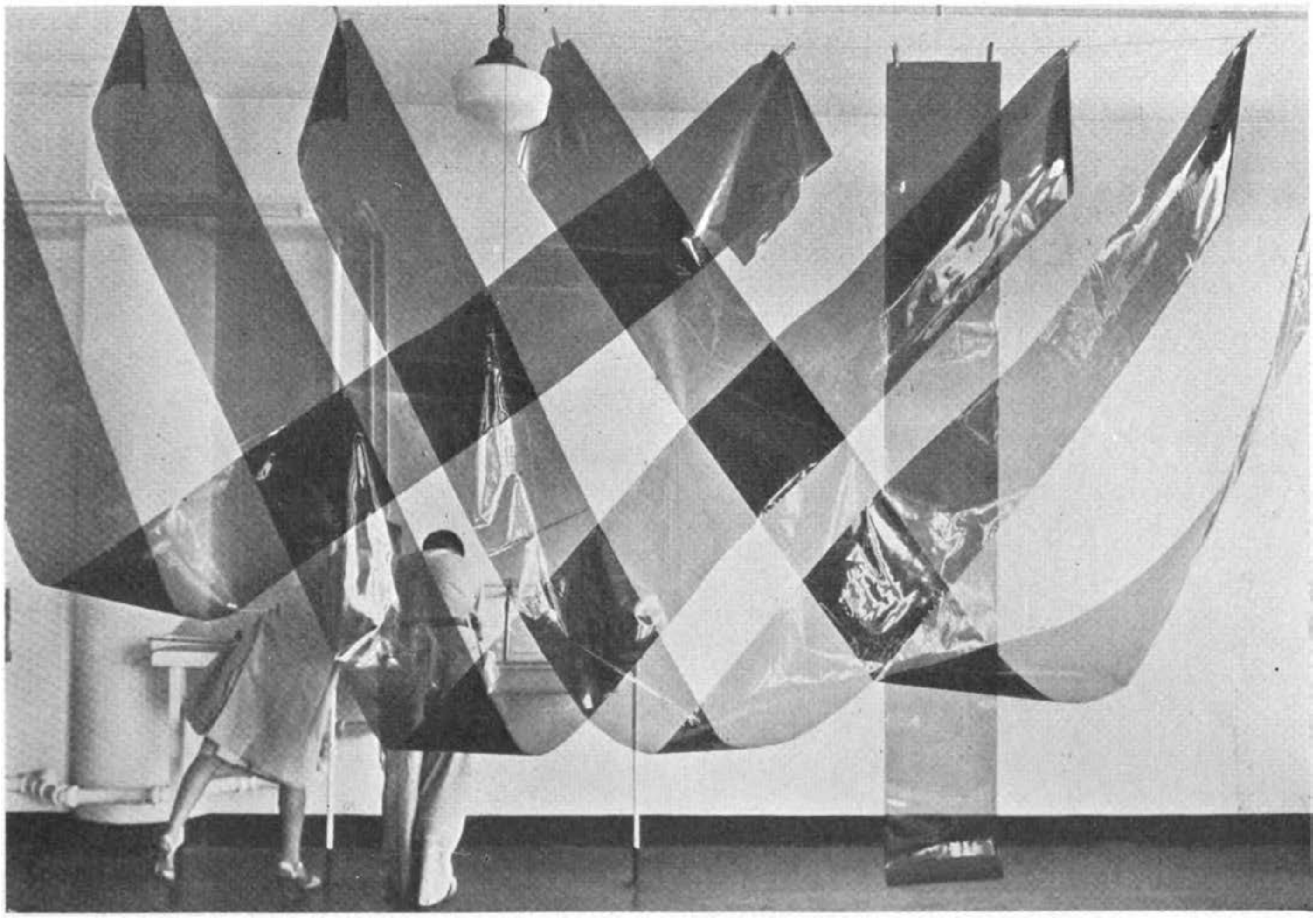

FIGURE 12.—Strips of Light-Polarizing Film Hanging in the Laboratory of the Polaroid Corporation, Cambridge, Massachusetts. The Strips Are Transparent Unless Two Are Crossed at Right Angles

couraging such cooperative exchange of information, while only 7 recognized that collaboration was essential because of interlocking technology. Because the small company tends to carve out for itself a unique technical position, the engineering work of 11 such companies has become more highly specialized, while 19 companies are faced by an increasingly complex art.

For the most part, the small company as represented by 34 of the 50 companies studied prefer to hire men with broad engineering training, while 5 had occasion to employ scientifically trained experts. Nine other companies, however, look primarily to one of the owners or a chief executive who is of the inventor type or genius for their technical inspiration and developments. On the other hand, 14 companies rely largely for their technical personnel upon long-service executives, while 19 draw much of their technical material from practically trained technicians or trade school graduates. Twenty companies emphasized the importance for their purposes of bringing men up through the ranks with company training, rather than drawing upon the supply of college-trained engineers, which is the resource of technical personnel for 11 other companies. Thirteen companies make a specific point of periodically bringing in new blood in the form of graduates fresh from engineering colleges.

Dependence Upon Outside Research Agencies

In spite of the fact that the small company recognizes the importance of research to the extent of training its own specialists or hiring engineering talent, the near-term objectives of all their research activities preclude their being totally self-sufficient. Naturally, the necessity for being unique in its field demands that the small company be self-sufficient in the matter of immediate product or process developments. However, it is for the longer-range type of development, anticipating the trend in the art or creating new knowledge, that these companies must turn to outside research activities.[2] Only 15 companies have found it advisable to adopt such long-term policies with regard to outside research.

Of the 22 companies which in supplementing their research efforts turn to the outside, 11 have acquired inventions from individuals, while in 12 instances inventions or technical developments were taken over from the companies of origin. In 3 cases new developments were acquired from technical institutions. For the most part, companies prefer to buy outright such developments, although to clarify the art or to obviate the duplication of research, 9 companies were willing to take licenses. Not infrequently the research staff may be regarded as a sieve for ideas brought in by others, and as such it enables the company to pay most attention to the more promising ideas.

Since the small company cannot for the most part devote time to advancing the art or acquiring technical knowledge for itself, it not infrequently turns to established research agencies or technical institutions. Only 8 were in such specialized fields as to have no occasion to do so; their fields were considered so uniquely their own that they knew them better than any agency to which they could turn. While 6 companies employed the services of an expert consultant, 13 made intermittent use of private laboratories. Twenty-four of the small companies in our sample had had recourse to the faculty and laboratories of engineering colleges, whereas 3 had turned to research foundations. The cooperative research carried on by trade associations had proved to be a resource for 11 companies where processing technique or technical problems common to an industry predominate. One company made use of governmental research activities through the National Bureau of Standards.

The use by small companies of the afore-mentioned research agencies appears to be more of the nature of intermittent consultation as evidenced by the experience of 19 companies. Twelve companies have periodically employed experts on retainer, while 10 have sponsored specific projects on a fee basis. Only 2 have financed longer-term fellowships through research foundations.

Professional-society activity proved to be a particular resource for the technical personnel of 19 companies whose participation the management actively encouraged. It is significant that the more self-reliant companies made a particular point of their dependence on following closely the current literature coming from the technical press.

Benefits from Cooperative Research Activities

A particular resource to the small company is the exchange of technical information and the accumulation of new ideas that comes through the informal contacts between engineers in their technical work or in the direct line of business. Twenty-seven companies spoke particularly of the technical activities that grew out of their relations with customers as a particular resource for new developments. Similarly 8 concerns had derived benefits in working out technical problems with their dealers. Thirteen companies had found a particular resource in the research activities of noncompetitors in allied fields, whereby they could adopt new developments to supplement their own technical activities and avoid the unnecessary duplication of research. On the other hand, 9 companies readily availed themselves of the opportunity to visit about through the plants of noncompetitors to keep them-

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[2] Industrial research laboratories of the United States. *Bulletin 104*. 7th edition. Washington, D. C., National Research Council (1940).

selves informed about new methods of production which would have a bearing upon the improvement of their own operations. In 6 instances companies whose business was largely on a contract basis and less dependent upon a specialized technology were not averse to discussing broad technical problems of the industry with competitors, or even to taking licenses for the use of specific technical developments.

Of marked significance is the resource that small companies find in the research activities of their suppliers and those from whom they purchase manufacturing equipment. Thirty-eight companies stressed particularly the advantages that come through the contacts with supplier's engineers or representatives in working out the specifications for raw materials particularly suited to their needs or in the advice given regarding the use of specially designed mechanisms, electrical apparatus or controls, or the like, which are necessary to the ultimate product but which are foreign to the company's own field of development. Likewise, the technical activities of equipment manufacturers have proved to be a resource to 13 companies where the mechanization of process is becoming more highly specialized. Nevertheless, the manufacturing requirements of 14 companies were sufficiently unique for them to design their own specialized machines. In 10 cases companies actually built their own machinery.

Significance of Research to the Small Enterprise

In brief, the picture presented by the small enterprise is, because of the necessity for uniqueness, that of a concern rendering a specialized technical service to larger units of industry, to discriminating customers, or to selected markets through the manufacture of a distinctive or quality product. This research aspect of such enterprise is strikingly borne out by the intimate customer relationship maintained in almost every instance where the proprietor, the active top executive, or a corps of sales engineers works closely with the engineers in other companies to develop new products or features particularly suited to the latter's requirements. Thus research, whatever may be the extent of organized fact-finding, is an indispensable resource to the small company through which it holds its place in the face of competition.

While their executives and technical personnel have become experts in some specialized branch of technology through continually having to meet new situations, the circumstances under which the majority of small businesses must operate preclude a long-range policy toward their technical activities and force them to look to the outside to replenish their technical resources and to keep abreast of progress in the arts and sciences. Accordingly, in spite of being manifestly

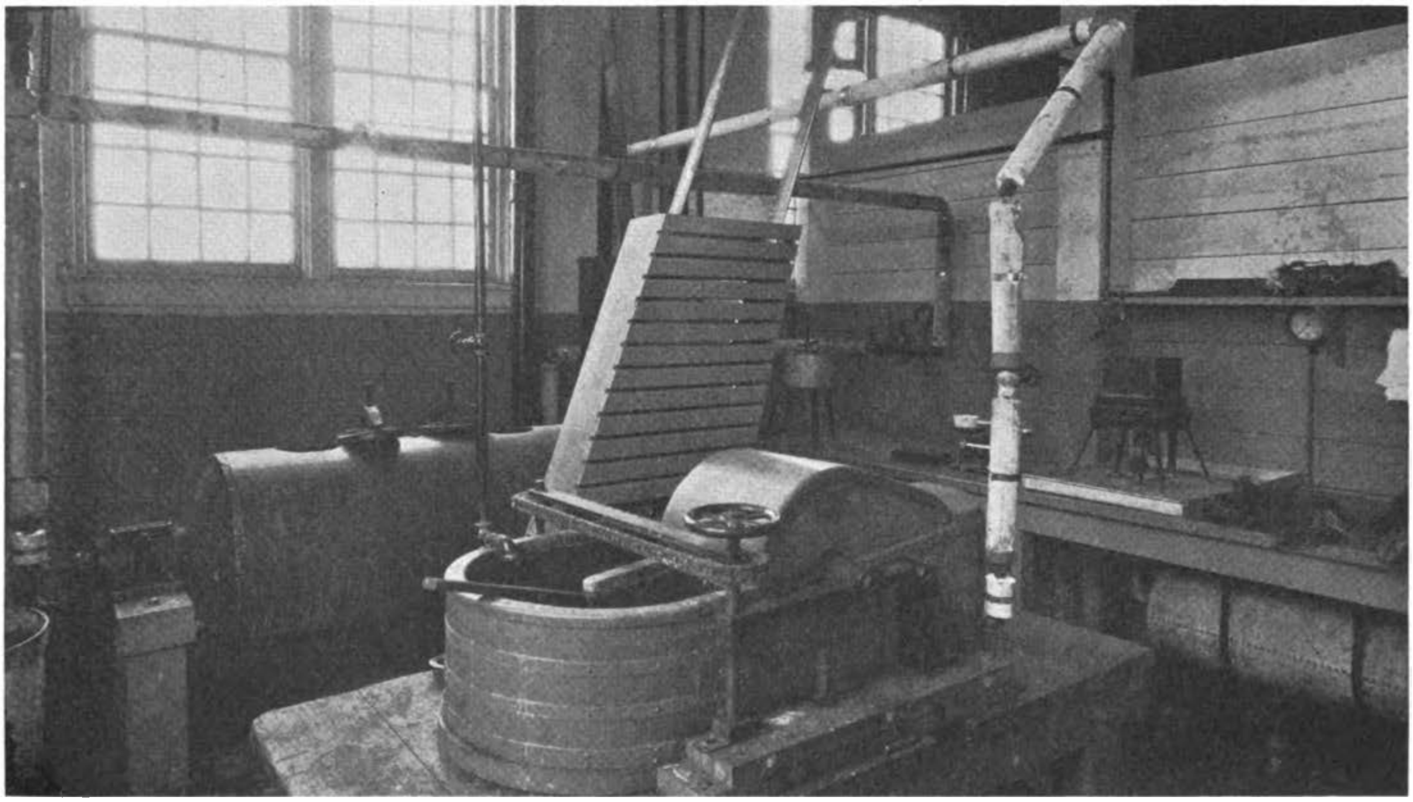

FIGURE 13.—Fiber Preparation Laboratory, John A. Manning Paper Company, Incorporated, Troy, New York

self-sufficient in its own field of technology, the small company must turn from time to time to consultants, private laboratories, and technical institutions for new knowledge, new developments, and advice on the application of allied technology to their immediate problems. An even greater technical resource is found in cooperative research or the informal exchange of information between their engineers and those of noncompetitors, suppliers of material or special apparatus, and manufacturers of process equipment. Participation in professional-society activities and resort to current technical literature appear to be most fruitful avenues for the small company to profit from the research of others.

Thus, research is in reality a triple resource to the small company. It acquires new technical facility from research conducted by outside agencies or allied industry; through its own organized fact finding it creates its specialized technical field; and by catering to the requirements of its customers it renders a unique technical service to industry and the community.

SECTION II

3. COORDINATION BETWEEN INDUSTRIES IN INDUSTRIAL RESEARCH

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ABSTRACT

This is a survey of the present cooperation between companies as to (1) joint activities in research, (2) the exchange of information, and (3) the publication of research findings. It is based on the activities of companies which represent many of the industries and industrial areas of the country.

Joint research carried on by industrial companies takes the form of (*a*) cooperation in the research activities of technical societies, trade associations, and the like, (*b*) cooperation with other companies in the development of a new product, a new process, or a new raw material which all the companies are interested in commercializing, and (*c*) cooperation in financing industrial research in universities and in government research foundation, and private consulting laboratories.

Research information is exchanged among industrial concerns through members of their staffs participating in the meetings and serving on the committees of technical societies, trade associations, and the like. The general policy is to encourage the publication of research findings which contribute to technical knowledge unless such a step would jeopardize a company's position or reveal proprietary secrets. Information about the organization, management, and administration of research in industry is exchanged at group meetings of industrial executives and of research directors.

Joint Activities in Research

Scientific and engineering societies and trade associations conduct many investigations which are so broad in scope and so general in interest that no one company would be justified in making the necessary expenditures for them. A number of interested concerns, however, will cooperate as a group in financing and supervising such investigations. They are generally conducted in university, government, or private laboratories and are usually concerned with (1) obtaining fundamental scientific and engineering data, (2) the development of test procedures and analytical methods, and (3) to some extent with finding new applications for raw materials.

Several companies may also engage in a cooperative research program directed toward the development of a new product, a new process, or a raw material. Most of the joint activities of this nature are carried on by a company and its customers or its suppliers of raw materials and equipment. This is a logical activity as each concern stands to profit from the successful commercial utilization of the new product, process, or raw material. Such cooperation is quite general among industrial concerns though it does not often represent a large part of their research activities. It is distinct from sales service or trouble shooting.

Within the past few years there have been many notable examples of products developed as the result of the joint research efforts of a number of companies. Among these are the sealed beam headlight for automobiles, in the development and production of which a nationally known electrical manufacturing company joined with equally well-known glass, rubber, and other companies. Another is the bullet-resisting tire, recently announced by the Ordnance Department of the United States Army, which has been a cooperative development of such major rubber companies as Firestone, Goodrich, Seiberling, Goodyear, and United States Rubber.

Many companies which carry on research cooperate with universities. Such cooperation generally involves either (1) fundamental scientific studies in the general fields of the company's interests, or (2) specific investigations with definite objectives and of a nature directly related to the operations of the company. The industrial concern usually provides only the funds for the work while the university provides the research facilities, personnel, and supervision. Fundamental scientific studies are generally set up as fellowships for students working for advanced degrees. Specific investigations usually require full-time trained personnel and administration with frequent reports to and conferences with the industrial sponsor. A number of concerns in addition employ faculty members as consultants.

Industry also supports research programs in private consulting and industrial research-foundation laboratories. These projects are generally of a specific, confidential nature with a definite commercial objective requiring energetic attack and early solution of the problem. Such laboratories as the Mellon Institute for Industrial Research, Battelle Memorial Institute, Arthur D. Little, Inc., are typical of such agencies.

There is some small degree of cooperation in research between industrial concerns and governmental laboratories. The projects are usually of general scientific nature and of interest to a number of concerns, all of whom contribute to their support. In the field of agriculture some national and state experiment stations cooperate directly with one or more concerns in the development and testing of new raw materials or of industrial products that may have applications in agriculture.

Some companies spend as much as 10 percent of their research budgets on cooperative research programs with university, private, and government laboratories. The usual figure, however, seems to be nearer 2 to 3 percent. There is occasional exchange of personnel on projects and of course considerable exchange of information in the form of conferences and reports.

Exchange of Information

The most general means of exchanging research information among industrial concerns is through participation in the meetings and technical committee work of technical societies, trade associations, and the like.

Many members of the industrial research staffs belong to technical societies and present their findings of technical value at the meetings of such societies.

These societies and associations also sponsor a great deal of committee activity which benefits industry as well as the technical professions and the public. This work is directed toward the formulation of industrial standards and specifications, testing procedures, analytical methods, and related subjects. New scientific and engineering data are also obtained through their cooperative research programs. Industrial concerns are well represented in the membership of these committees, contributing the time and expenses of their representatives as well as much of the information needed.

Policies on Publication of Research Findings

The general policy of enlightened companies seems to be to encourage their staffs to publish research findings when (1) these results are of broad interest and represent real contributions to technical knowledge, and when (2) such publication does not jeopardize the company's patent position or reveal proprietary secrets. Many research results appear first in patents and are later generalized either in articles in the technical press or in papers presented before technical societies.

Technical items of current interest are also published in some 90 industrial research laboratory house organs as listed in the National Research Council's Bulletin No. 102 entitled "Industrial Research Laboratories of the United States."

The Industrial Research Institute

As indicated above the most usual type of information that is exchanged among the research organizations of industry is of a technical nature. Within the past 3 years, however, a new activity has appeared for the exchange of information on the organization, management, and administration of research in industry. This work is being carried on by the Industrial Research Institute, affiliated with the National Research Council. Its purpose is to promote, through the cooperative efforts of its members, constant improvement of methods and more economical and effective management in industrial research.

Industry as a whole has been convinced of the need for doing research but still has much to learn about how best to do it. Little information or experience is available on how to organize and manage research so as to obtain results in the most efficient and economical way. A research organization has peculiar characteristics of function, operation, and personnel that do not easily lend themselves to customary business management methods. Company heads are nevertheless justified in demanding results with economy from their research organizations since their operations are constantly growing in terms of capital investment, annual expenditures, and number of personnel.

This situation led a group of research directors to seek the aid of the National Research Council about 3 years ago in forming an Industrial Research Institute for the cooperative study of common problems of research management. Maurice Holland, director of the Division of Engineering and Industrial Research of the Council, has been largely responsible for developing the idea and organizing and guiding the Industrial Research Institute that resulted. The institute started with 14 company members and now numbers 33 that are widely representative of types of industry and of the industrial areas of the country. The institute is designed primarily to serve the middle-sized research organizations rather than the largest ones, whose practices are fairly well developed. The laboratory staffs of most of the member companies number under 100 persons.

The institute has found that the best means of accomplishing its objects is through periodic meetings at which common problems are discussed in an informal manner. Such matters as organization, personnel management, project selection, scheduling and control, budgeting and accounting, selling research, university relations to management, suggestion systems and patent procedure are considered. Extended studies are frequently made by members of the institute or by its staff on subjects of special interest. Tours of member-company laboratories are often a feature of the meetings. The institute meets 3 or 4 times a year. The round table method of discussion is used to promote informality, and the proceedings are confidential.

The institute provides practically the only source of up-to-date information on the organization, management, and policy problems of industrial research organizations. Through its programs and the close personal associations made possible by its meetings, the members gain help in solving current problems, confirm their present procedures, or learn better ways of doing the job. This exchange of information and experience directly leads to more efficient operation of research organizations and consequently to better and more tangible results in shorter periods of time and at less cost. These results in turn mean that research activities are more fruitful and timely and hence financial returns are realized more quickly than would be the case otherwise.

The processes, methods and materials used successfully in one industry may often be adopted satisfactorily in an industry of quite different characteristics. The institute provides its members with an opportunity to learn of such possibilities as it is made up of a variety of industries whose representatives confer frankly with each other.

Activity in the institute is also a constant source of encouragement and inspiration to the members in the better conduct of their jobs, gained from association with other men of attainment, responsibility and broad vision.

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SECTION II

4. TECHNICAL RESEARCH BY TRADE ASSOCIATIONS

By Charles J. Brand*

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ABSTRACT

Successful research by trade associations should benefit both association members and the consumers of the members' products.

Trade associations use various agencies for conducting research. A large number of associations maintain their own well-equipped, ably staffed laboratories; many use commercial research laboratories; some rely on university fellowships or financial grants to educational institutions; and others obtain the assistance of Government agencies having research facilities, such as the National Bureau of Standards. Many other methods are available and used.

Among important research projects now being carried on by trade associations and, according to a recent survey, in the order mentioned as to frequency, are the search for additional sources of supply of standard materials or for new materials, efforts to improve standard products, investigation of outlets for the industry's products, and search for new products that the industry can successfully manufacture and sell.

A great variety of useful work has been done. The technical research activities of the American Institute of Steel Construction, the National Canners Association, The National Fertilizer Association, the National Lumber Manufacturers Association, the National Paint, Varnish, and Lacquer Association, and the National Sand and Gravel Association, are briefly discussed, however, as typical examples of the great volume of research being carried on by trade associations.

A major problem confronting trade association technical research is that of financing. Unless immediate practical results permit prompt returns to the industry, interest in research projects wanes and financing becomes increasingly difficult. Fundamental research is seldom of such a nature that the problem can be quickly solved. Financial arrangements should insure reasonable continuity of research projects for periods sufficiently long to permit complete exploration of the possibilities involved. It should be financed, whenever possible, from the general funds of the association in order that all members may have equal rights in the results.

The results of trade association research should be made available to the members and the public as rapidly and completely as the definite findings warrant. Statistical valuation of the results obtained is not possible, but a great amount of benefit to the public at large has been obtained. The special equipment and trained personnel of trade association research organizations will be quickly and efficiently available to serve the people in any national emergency.

Technical research is undertaken for the purpose of producing new or better articles of commerce, reducing their cost, or finding new raw materials, or new or increased uses for finished products. Trade association technical research, to be of the most value in our national economic program, must, of necessity, produce results beneficial to the public as well as to association members. Naturally, assistance to association members must be the first objective. Unless members receive some tangible benefit, it is impossible to obtain their continued financial support for research.

The determination of a trade association to engage in technical research is customarily made only after careful study and consideration of the many problems involved. Each project selected for investigation must be of interest and potential value to each member of the association. Great care must be taken to see that the results to be expected from some particular line of research are not of such character as to benefit only one member of, or a select group in, the association. Trade associations include member companies that have developed widely varying yet long-established business principles. Executives of these companies range from rule-of-thumb operators who have risen from the ranks of manual workers to specially trained and highly educated scientists. The opinions and psychologies of men so varied in training and experience are likely to be very difficult to reconcile initially. If technical research is to be maintained, the first necessity, and the ever-present problem before the trade associa-

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*Mr. Fred S. Lodge, technical staff assistant of the association, has rendered valuable assistance in the collection and preparation of material.

tion executive, is the establishment and maintenance of a ground of common interest in research activity that is acceptable to a majority of the members.

That which benefits the producer benefits the consumer. The producer may be enabled through technical research to reduce costs or to manufacture a superior article at the same price. In the latter case the customer benefits directly by receiving better value for his money. In the former, the customer will eventually receive the benefit of cost reduction, and competition will probably operate to make reasonably certain that he receives it promptly. Unless the consumer benefits from the result of technical research, an incentive to increase consumption is lacking, and this is one of the main objectives of trade association activities.

While trade association technical research must always be designed to render its greatest benefits to the members of the association, and to their consumer customers, other members of the particular industry involved almost always benefit to some degree. Any new, better, or cheaper method of production can at best be restricted to association members only in part. Even if the exact product or process cannot be duplicated legally by nonmembers, for whatever reason, such competitors are stimulated to substitution or imitation. Oftentimes the substitute or imitation equals or surpasses the original. The general plane of quality is raised and the Nation benefits.

Technical research carried on by one industry may vitally affect other apparently entirely unrelated industries. Substitutes for standard commodities produced by one industry may be developed through technical research in another. Stainless steels, for instance, have almost completely supplanted some nonferrous metals and alloys for many uses where ordinary corrosion is an important factor. An industry may suddenly find that the entire outlet for its product has been captured by some other industry that it did not previously regard as in any sense competitive. The partly supplanted industry must find other outlets, better its methods or its products sufficiently to compete, or lose its market. Its entire economic existence may be at stake. The balance is upset and must be reestablished. Often such an industry must turn to cooperative association research of one kind or another in order to solve its new problems and continue its operations. This situation is evidenced in the relation the artificial refrigeration industry bears to the natural and artificial ice industries. The expense of individual research effort is often prohibitive; a pooling of the knowledge, the experience, and the resources of an entire industry may be essential to the maintenance of its research activities.

Types of Research

Any research project that has for its object the development of a new source of a raw material important to an industry, or of a new raw material usable by all members of the association, presents an acceptable undertaking. It might well be that an individual association member would not elect to avail himself of such a new source or new material and would thus seem not to reap a benefit. In such case, however,

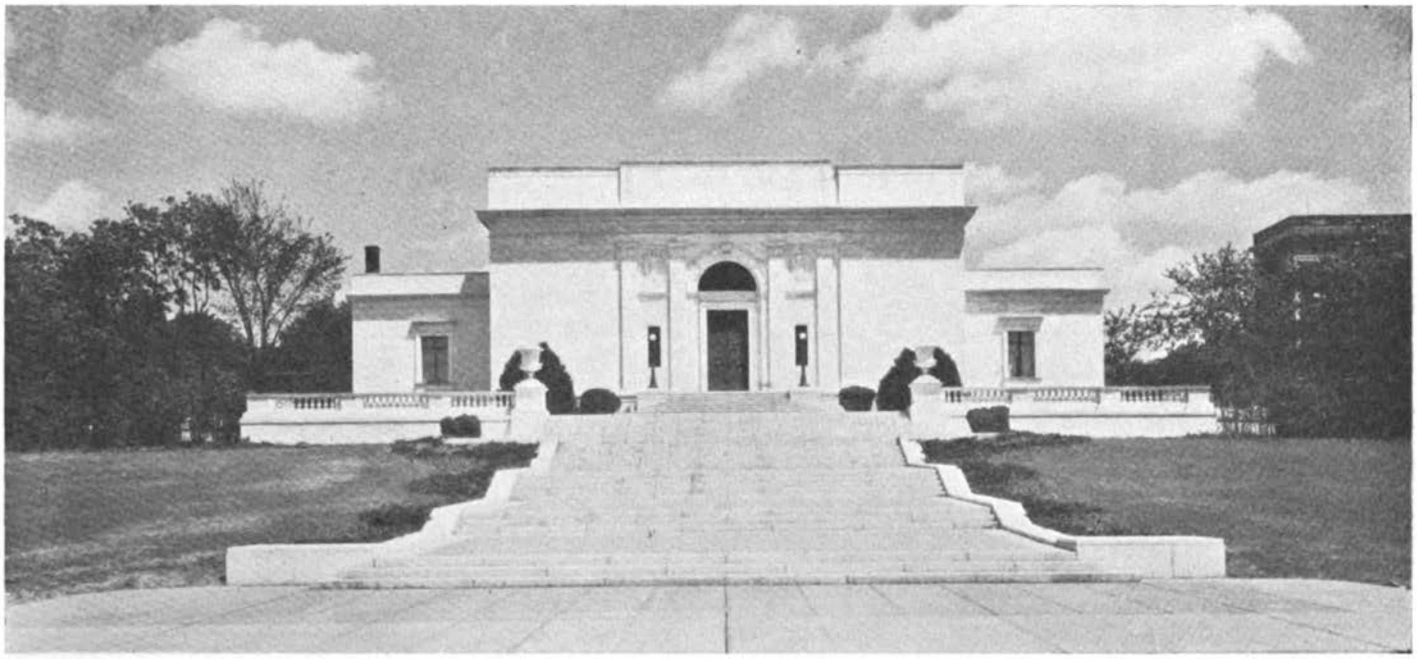

FIGURE 14.—Laboratory and Headquarters of the American Pharmaceutical Association, Washington, D. C.

competitive purchasing pressure would be transferred from his raw material source of supply insofar as his competitors' purchases were diverted to the new source or material, and he would benefit proportionately. As reported in a survey of trade association activities made by the Trade Association Department of the Chamber of Commerce of the United States, technical research on materials already in use, or on the use of new materials, was carried on by 90 of the 330 trade associations reporting.

New Products Developed

Trade association research is approaching the field of private endeavor when it concerns itself with new products, unless such new product can be made generally by the members of the association from raw materials ordinarily used or easily obtainable. However, research that may lead to the development of a new product which logically can be produced in conjunction with current operations of industry members in general may be of inestimable value to an industry and, if practical for use by all operators, presents a legitimate type of research for trade associations to undertake.

Research projects of this character, carried on by associations of the coke and gas producers have been instrumental in salvaging volatile products from coal that were formerly wasted into the air, and from which are produced innumerable new and useful chemical compounds. The sale of joint products or byproducts thus obtained reduces the cost of manufacturing the major product. That trade associations recognize the value of research aimed at the discovery of new and improved products is evidenced by the fact that, in the United States Chamber of Commerce survey already mentioned, 84 associations report themselves engaged in research of this character.

The National Lumber Manufacturers' Association early in its research work discovered that projects directly financed by members had to be limited, for practical reasons, to such as had rather immediate commercial application. In 1933 the association founded as an auxiliary the Timber Engineering Company. This company acquired certain patents and was constituted not only to develop and license the use of the devices covered by these patents—mostly timber connectors—in construction practice throughout the United States, but also to engage in research to develop improved methods and devices for timber construction. This activity has continued, and as a result the Timber Connector System of Construction, unknown in this country prior to 1933, has been successfully used in more than 10,000 structures of various kinds in this country, as well as in foreign countries.

This type of organization, operating separately though controlled by the association, has assured continuity of research projects requiring several years to complete. The income from the licensing of patents furnishes funds for additional research. In the case of the Timber Engineering Company, it has already repaid or is in position to pay from its net working capital all the funds originally furnished to acquire the patents and initiate the activities of the company. Of greater interest, however, to the lumber industry is the fact that the system of construction controlled and improved by the Timber Engineering Company has been instrumental in increasing the sales of lumber many hundred million feet. This combination of commercial activity and research through the trade association is a particularly satisfactory one. All members of the industry and the public benefit from the research on equal terms, and consumption of the industry's product is increased.

Another research activity of interest in the building and construction industry is that carried on by the American Institute of Steel Construction, Inc. Having as a goal reduction in the cost of steel buildings, bridges, and other steel structures, its early efforts were designed to bring about standardization of steel shapes and sizes. Intelligent standardization of this type must include a great deal of physical research into the properties of the various steel shapes and their reactions under stress so that those selected as standards will most efficiently carry the strains and stresses of the structure of which they are a part. The best products of engineering design were subjected to testing-laboratory proof. The National Bureau of Standards and the testing laboratories of certain engineering colleges collaborated with the Institute in this work. Other work was carried on in collaboration with the same institutions in connection with the strength of riveted steel rigid frames and welded steel rigid frames.

The institute's research program of welding research has resulted in the development of an economical steel floor design which greatly reduces the dead weight on bridges and other steel structures using floors of that type. Incidentally, better fireproofing qualities have been obtained. The rigid frame type of construction developed by this research permits a reduced perimeter for a building with a given vertical clearance and a given clear floor space; more economical provisions for wind stresses; greater speed and lower cost of erection; more economical hoist installation, and reduced maintenance costs. All of these improvements ultimately benefit the steel consumer either in the form of a lower investment cost or a cheaper upkeep. The institute issues bulletins giving detailed specifications of welding practices in building construction so as to permit the construction industry to make the best possible use of its research findings.

Quality Standards Improved

Research concerning the improvement of standard products is one of the least controversial projects that trade associations can undertake. Almost without exception, manufacturers will agree that anything which raises the general quality level of an industry's products will benefit members. Nothing promotes public appreciation and approval so much as a reputation for excellent quality in an industry's goods. Thus the unquestioned acceptance of all commodities packed in tin cans is an excellent example of the effect that can be achieved by association research to improve quality. Again, research by the Underwriters Laboratories has been of such high character as to make their certification of fire-fighting and fire-prevention equipment acceptable as standard by the public, by official bodies, and by insurance companies.

New Uses for Products

Another most appropriate type of research work for trade associations is the development of new outlets for standard industry products. Whenever an industry's production or even its capacity for production equals the demand for its product, the competitive struggle of that industry becomes intense. Any new outlet for its products relieves the pressure due to overproduction and tends to stabilize the industry. A well-known example is the use of the modern synthetic plastics, of which Bakelite is an example, to displace the various kinds of insulators used in making electrical equipment. These same plastics are also replacing many ornamental metal stampings, metal caps and seals, corks, glass covers, and innumerable other products. Association research is not believed to be responsible for the development of these new uses of synthetic plastics, private research is to be credited for their discovery and utilization. Trade association research has, however, been forced to undertake the development of new outlets for the products supplanted. Of the 330 trade associations reporting in the Chamber of Commerce survey, 54 include in their research programs the search for new uses for present products. It must be remembered that technical research is only one branch of association research on such a problem; business research, studies of marketing conditions, and of consumer resistance, and the like must accompany the practical technical solution of the problem if an industry is to benefit.

Research on industrial processes and methods usually can best be undertaken by trade associations when comparative uniformity of production methods exists. The canning industry furnishes a typical example of such possibilities. In the main, canned foods are packed in airtight containers, and preservation of the contents depends on sterilization after packing. The quality of the contents and the suitability and attractiveness of the package largely determine competitive success or failure. The goal to be achieved by proper processing is the protection of human health. The industry, through its trade association, has not hesitated to provide adequate funds to support a well-equipped laboratory.

Technical Research Agencies

Trade associations carry on technical research in a variety of ways.[1] In selecting the type of agency best suited to carry on an industry's technical research, the nature of the problems to be solved must receive careful consideration. If only improvement of product or process is contemplated, perhaps the most effective plan is the establishment of an association laboratory. If standardization of members' products is the goal, coordinated study and research within the members' own laboratories may be sufficient. If an entirely new field of fundamental science is to be explored, if expensive precision equipment must be used, if policy requires scientific sponsorship more authoritative than that of the technicians of the industry, then the laboratory of some well-known university may afford the best agency to use.

If a particular problem can be solved, as many can, by oft repeated trial and error methods, one of the best available organizations is the commercial consulting laboratory, the analytical accuracy and techniques of which make them peculiarly suitable for this type of research. If the answer is obtainable only by means of accurate determination of minute variations in physical measurements, some agency such as the National Bureau of Standards at Washington may be the best choice.

If the problem is that of meeting State or Federal regulatory requirements, grants of financial aid to some governmental agency for research in that field may not only furnish the solution but may result in official recognition of the results.

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[1] The following News Letter was recently issued by the National Association of Manufacturers:

"Thirty-one percent of the National Manufacturing Trade associations in the National Industrial Council conduct scientific research activities, according to a survey just completed by the Council in cooperation with the N. A. M. Advisory Committee on Scientific Research, of which Dr. Karl T. Compton, president of the Massachusetts Institute of Technology, is chairman.

"Charles J. Brand, executive secretary of The National Fertilizer Association, is chairman of the N. I. C. Committee in charge of the survey.

"Of the 113 associations in the national manufacturing trade group 35 conduct research activities and 11 have their own laboratories or cooperate with others in supporting laboratories. The average annual research budget of 27 associations reporting specific figures was $36,960. The median budget was $25,000. Two associations spend more than $100,000 a year.

"An average of 10 persons are employed in the laboratories operated by the associations reporting.

"Twenty-one of the associations finance research projects at universities, 7 at research foundations, and 3 at commercial laboratories.

"Most of the laboratories reported were established in the decade between 1920 and 1930.

"Approximately 34 percent of the associations take out patents on the products of their research activities. In the most instances, the patents are assigned to the association.

"Ten associations distribute information on the results of their research to members only and 25 make the results known to the public generally."

Trade Association Laboratories

Industries confronted with many technical problems are inclined to support technical research generously. Trade associations within such industries generally maintain their own research laboratories. These can usually handle most of the types of research mentioned. We find recorded in the Chamber of Commerce survey that at least 36 trade associations maintain their own research laboratories. These laboratories are manned by staffs having a combined personnel of over 425 chemists, physicists, and engineers, and about the same number of assistants without technical education but with excellent experience and training in laboratory technique. These laboratory staffs vary from some numbering only a technologist and one helper up to others employing 116 scientists with a large number of assistants.

Research Promotes Consumption of Canned Foods

The National Canners Association affords an excellent example of industry and public benefit derived through research carried on in an industry's own laboratory. This trade association laboratory, founded in 1913, was one of the first to engage solely in research. This association maintains a central research laboratory in Washington, with branches in the canning areas on the Pacific coast and a traveling laboratory for use wherever needed. In the early days of commercial canning, spoilage of canned food was all too common. It was ordinary practice to add some chemical for the purpose of preventing bacterial growth and resulting decomposition. The canning industry met and solved successfully difficult problems that arose from the fact that a few types of canned foods seemed particularly susceptible to contamination by so-called "food poisons" that were occasionally serious in their effects.

When the canning industry established its research laboratory, one of the ablest food chemists of the country was placed in charge of it. This scientist had until then been in charge of one of the Government laboratories engaged in food research and regulatory administration. Intensive studies were at once initiated on the methods necessary to insure the sterilization of canned foods without recourse to chemical preservatives. Length of cooking and the temperatures necessary to obtain complete sterility of containers of every size were carefully determined for each type of food product packed. Variations necessary in the processing of acid as compared with nonacid foods were carefully worked out. Lacquer linings for many types of tin cans were investigated and individually developed for use with each canned product likely to affect ordinary cans. Chemical changes occurring during canning and processing were studied with particular reference to the vitamin content of the various foods.

The industry quickly availed itself of the association laboratory's findings and put its recommendations into effect in processing. Spoilage of canned foods virtually has become a thing of the past. The industry has benefited in many ways; the expense of replacing spoiled goods has been eliminated, and canned food products of reputable manufacturers are now universally accepted as sound and wholesome. The public has benefited through having made available a very wide variety of wholesome foods at lower costs, with danger to health or life almost completely eliminated. No better example of the value to be obtained from a trade association's operation of its own technical research laboratory can be cited.

Paint and Varnish Research

Another typical example of trade association research is the work carried on by the scientific section of the National Paint, Varnish and Lacquer Association, Inc. This association has its home in an historic mansion in the center of Washington which contains its offices and laboratories.

Research in this organization follows four principal lines: (1) Determining the actual causes of claimed failures of the industry's products; (2) investigating new oil-bearing plants; (3) examining new raw materials such as pigments, resins, and balsams; (4) evaluating finished products of the industry as to durability and other physical properties in order to develop new fields of use and to increase consumption. Analytical work, publicity through lectures, and compilation of pertinent references in the technical literature are also a part of the scientific section's activities.

The research work of this association is done by a staff of eight members under the guidance of an advisory committee of the association. It affords an illustration, too, of some of the additional work that naturally eventuates from research work. In 1939 the staff wrote some 9,000 letters generally in answer to technical inquiries and entertained some 1,500 visitors, many, if not most, of whom wished to discuss their technical problems.

Commercial Research Laboratories

Numerous excellent commercial laboratories have been established in this country. Their activities cover not only the control of technical processes in privately operated establishments, but research on practical operating problems and the conduct of independent scientific research as well. Many important technical processes have been discovered and perfected in commercial laboratories. The alloy of nickel and chromium, composing the heating elements of most of our household electrical appliances, is the result of research in such a commercial laboratory. Some 24 trade associations reported in the United States Chamber of Commerce survey that they utilize this type of organization to carry on their technical research.

University Fellowships and Grants

Fellowships at technical schools and universities are sponsored by 21 trade associations. These fellowships are generally founded in an institution where some member of the faculty is known to be especially versed in the particular research problem involved. The fellowships are usually extended to graduate students working for higher degrees. For a relatively modest sum, half of a fellow's time is obtained and, in addition, the consulting services of the professor are available. Such arrangements are particularly effective if the boundaries of the problem are well defined so that a planned line of procedure can be laid down. They are not as effective in fields where the problems are ill defined. Similar to these fellowships are money grants made to members of university faculties to enable them to pay for supplies, apparatus, and laboratory assistants for research on problems submitted for study. In such cases it is often not possible to arrange that a specific amount of time be devoted on projects undertaken. Usually such research is secondary to the regular university work of the researcher and must be done by him as time permits.

The National Fertilizer Association, for example, has employed these methods for research with excellent results. Funds for fellowships in agronomy were made available to a number of universities where the college of agriculture and the State agricultural experiment station were jointly operated. The problems selected for these research activities were not only of scientific interest to the faculty, but their successful solution also promised benefit to agriculture in general. The problems naturally concerned some phase of plant feeding because the fertilizer, or plant food, industry was supplying the necessary funds. In carrying out some of the projects, grants were also made for traveling and other expenses to representatives of the United States Department of Agriculture who cooperated and assisted in coordinating the various studies. At least a dozen such projects were supported, some of them lasting several years, and in some years several thousand dollars were appropriated.

The most extensive and probably the most important research carried out under these plans was the study of the proper methods for applying fertilizers to various crops in order to produce the most effective results. A number of fellowships and grants were established for this purpose and, in addition, research projects covering

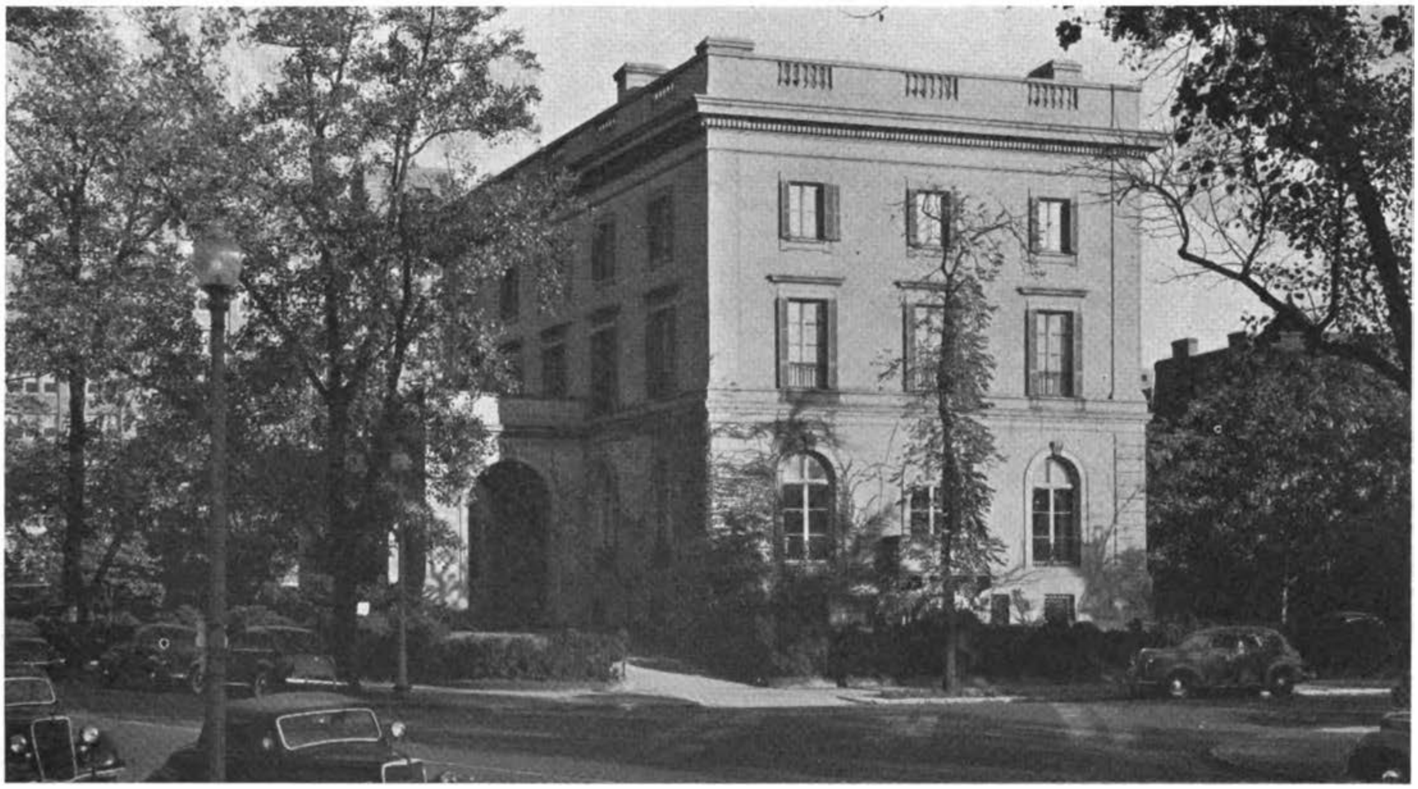

FIGURE 15.—National Paint, Varnish and Lacquer Association, Washington, D. C.

some particular crop or particular phase of fertilizer application were suggested to other colleges and agricultural experiment stations.

As the investigations proceeded, other interested organizations—the American Society of Agricultural Engineers, American Society of Agronomy, American Society for Horticultural Science, and Farm Equipment Institute—joined The National Fertilizer Association in forming a National Joint Committee on Fertilizer Application to assist in the program. The project has grown from four experiments on two crops in 1929 to 152 experiments at 73 locations in 23 States on 29 crops in 1939. Information of incalculable value to the farmers of the Nation has resulted from this extensive research project and has been disseminated to them through all available channels.

Governmental Research Agencies

The Federal Government maintains a large number of research laboratories from which help may be obtained in conducting research along lines that promise results redounding to the public good. For instance, the laboratories of the Bureau of Agricultural Chemistry and Engineering have been most helpful in working out problems of general interest. The four new regional research laboratories now under construction by the United States Department of Agriculture will no doubt be anxious to render similar assistance under suitable cooperative arrangements.

The Government agency most frequently called upon to aid trade-association research is probably the National Bureau of Standards. This agency, as its name implies, is most important in standardization research, but arrangements can be made with it to supply research associates for work on particular industrial problems. More often, however, a grant in money is made to the Bureau to provide funds for a specified task. One particularly important phase of the Bureau's work is the preparation and distribution of standard analytical samples and standard test specimens. The analyses and physical properties are carefully determined by the Bureau so that they can be used by individual laboratories to check the accuracy of their own methods and determinations.

For many years the National Sand and Gravel Association has sponsored research in connection with the use of the industry's products. Comprehensive studies have been carried on concerning the size, shape, porosity, and other physical characteristics of the aggregates used in concrete, in order to determine those qualities best adapted to particular types of construction.

The ever increasing importance of the construction of concrete highways in the defense program of the Nation undoubtedly would have made this particular research project one of public necessity if the trade association had not already instigated it. The Public Roads Administration and the Bureau of Mines are Federal agencies that have cooperated extensively in solving these research problems. The building industry, the landlord, and the home-owning public have all benefited in better, safer, and more economical buildings as a result of this trade association research.

Collection and Distribution of Data

One very important research service that a trade association can render to its industry and the public is the collection and dissemination of research data pertaining to the industry and its products. Thousands of research organizations or workers are scattered over the world. Often their findings are published only in some foreign periodical or in some obscure or inaccessible medium. Even if the work is mentioned in one of our scientific abstract journals, the significance of the data may be lost by an abstractor who is, himself, unfamiliar with the problems of the particular industry. Some trade associations review all available domestic and foreign publications that appear to have even remote application to their industry and keep their members advised of any new research data or developments that seem worthy of consideration.

In addition, experimental research agencies on occasion make new data available even before publication. Frequently the association is able to pass such information on to the industry. An excellent example of this type of trade-association research activity is a publication just issued by the Bureau of Raw Products Research of the National Canners Association. This bulletin of 143 pages summarizes the recent research work done by all the State agricultural experiment stations on all canning crops. Such subjects as cultural methods, varieties, fertilization, pest control and diseases are included in the abstracts presented, bringing into one book all the results of research along these lines from the 48 stations.

Financing Research

The problem of financing a technical research program for a trade association is often very difficult to solve. The earlier research projects were usually financed by voluntary subscriptions from the larger enterprises in an industry. This sometimes proved unsatisfactory, the donors often felt that the results should be reported only to them and hence objected to noncontributing members receiving the benefits of the research. Such methods are still used in some instances, however, where the contributing members have enough confidence in the project to believe they will receive sufficient benefit to warrant the expense, even though others also benefit. In other cases, manufacturers of raw materials or other basic supplies for a second industry engaged in processing and distribution may provide funds for research to the trade association of the second industry. The solution of the research problem thus financed would be expected to result in increased use of the material and hence in increased production by the donors. The manufacturers of tin cans, for instance, lend substantial financial support to the Canners Laboratory of the National Canners Association.

In general, research appropriations should be allocated from the general funds of the association and results should be made available to all members. Care must be taken to see that funds so allocated are sufficient to finance the laboratory or other research agency adequately for the work it is to undertake.

Seventeen trade associations out of thirty-six, answering a question in the Chamber of Commerce survey as to what was their greatest handicap in pursuing successful research, stated that it was lack of sufficient funds. A deficient budget may cause delay or even abandonment of a project when ultimate success seems nearly assured and a small additional expense promises the solution. Contributors are likely to become disgruntled and withdraw their association support when such a condition exists, instead of having the broader vision to carry on.

Research—A Long-Range Activity

In considering the funds necessary for research, thought must be given to the time element. Very few research investigations can be completed in one year. Reasonable assurance that funds will be made available until a piece of research can be completed is very desirable. The scientist can then plan the thorough and complete program that is so often necessary for the successful solution of a problem. If he must work under the handicap of feeling pressed for time, knowing that in so many months his work must terminate whether successful or not, he will be apt to take short cuts and may miss the necessary step that will insure a satisfactory product or process. If time is all important, sufficient financial provision should be made immediately to sustain as large a staff of scientists and technical aides as can effectively work on the project. If a mass of collective experience is necessary to "prove" the process, a well-organized corps of workers is often successful in saving much time. In many types of investigation, however, continued individual endeavor is the only practical method of approach. Such types of research may require many years to complete, and if undertaken by trade associations, the time requirement must be thoroughly understood and appreciated by the members.

Trade associations that are carrying on research projects satisfactorily attribute their success largely to adequate financial support both in amount and duration.

Coordination of Research

In most trade associations individual members will be found who are carrying on private research. Cooperation with them is essential to prevent needless duplication. This does not necessarily mean that the individual member must divulge the valuable results of successful private research. More often it means that private research has developed negative results along some apparently possible line of approach to a problem, and an unnecessary expenditure of effort and funds by the trade association research staff can be avoided if this fact is made known.

In many cases, too, private industry will be willing to share its research results with the trade association in order to hasten progress and promote the general welfare. The extent to which this is feasible naturally depends on the particular competitive commercial advantage involved. In general, it is believed that there is much greater exchange of this type of information than formerly was customary. Private enterprise is more inclined at present than in the past to encourage its scientists to publish the results of their technical studies.

The mutual problems of industrial scientists are more freely discussed by them before the meetings of their respective scientific societies than formerly. Publica-

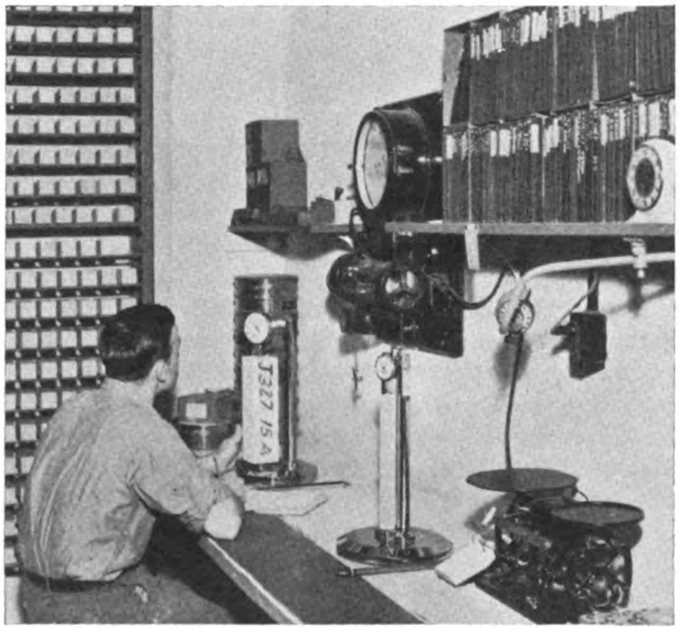

FIGURE 16.—Laboratory for Investigation of Length Change in Concrete, Portland Cement Association, Chicago, Illinois

tion of patents often reveals information of general interest and value. Perfected analytical technique makes possible much more intelligent investigation of raw materials and products. All of these factors are taken into consideration and are used by trade association research agencies in furthering their own work through deciding what not to undertake as well as what path to follow.

The Trade Association Research Committee

One important factor in the coordination of trade association technical research is the research committee of the association. This committee should be charged with the direction of the research laboratory if there be one, the stimulation of pertinent research by State and Federal research agencies, and the dissemination of information regarding research. The director of research, through the executive officer of the association, acts as the agent of the committee in these activities. The membership of a research committee should include representation from the outstanding technical, production, and sales executives of the association membership.

Only by such broad representation can the research program be properly envisioned and prosecuted. Results of technical research are commercially worthless if they cannot be utilized practically in production, or if the resulting products cannot be sold. Members of this committee should be able to see beyond the particular problems of their own enterprises and to understand the necessity of considering problems common to the industry. The research committee must have frequent meetings with the director of research and members of his staff so as to stimulate and direct the work along lines of most value to the industry.

Another function is to evaluate the research results practically at periodic intervals so as to decide what information already obtained is of sufficient importance to be disseminated to members, and in what manner it can best be utilized.

State engineering and agricultural colleges and experiment stations and many other educational organizations are often eager to have worth-while research problems suggested to them that will afford opportunities for thesis research by undergraduate and graduate students, or for more extensive institutional research. This provides a splendid opportunity for a research committee to function and to be of great assistance to its industry in establishing sound public relations. The Plant Food Research Committee of The National Fertilizer Association is made up of competent agronomists and chemists employed in the industry. This committee meets frequently to discuss the unsolved agronomic problems facing American agriculture and to plan ways and means of attempting their solution. In some instances the committee has sponsored research on its own account. More often it has been instrumental in arranging for studies to be undertaken by such agencies as State agricultural experiment stations. The committee often provides fertilizers and fertilizer materials and other aids in carrying on the work.

Patents

The question of patents does not often rise in trade association technical research. So many individuals are usually involved in any piece of such research, through suggestions, advice, or contributed experience, that even a new process or product can scarcely ever qualify as the patentable idea of any one individual or group. If a patentable feature should be developed during a piece of trade association research and a patent is granted, all members of the association would, of course, be privileged to use the patent without any royalty or fee. Others should be permitted to use the patent under license and appropriate fee unless such use would be definitely contrary to the interests of association members who bore the necessary expense of conducting the research involved.

Access to Research Results

The results of trade association technical research must be made freely and fully available to all members of the association. As discoveries are made, the facts should be made known to all members alike as soon as their practicability is determined. If a laboratory is maintained, members should have free access thereto for the purpose of first-hand demonstrations or conferences. Care must be taken that only such information is given out in personal interviews as has already been circulated to members, at least in general terms. To report a discovery to one member in advance of others, or to sequester information from any members, would manifestly be unfair and would very quickly disrupt the research program. After a general announcement to members of a research achievement, it seems perfectly proper to discuss any details thereof with any member who may take the trouble to visit the laboratory or write for further information. The method of acquainting members with research progress can best be determined by the research committee. If the association membership is large and its research activities are extensive, it may be desirable or necessary to publish printed bulletins to be kept for reference. These may be supplemented by mimeographed letters or releases. Keeping the membership informed of research progress, either achievement or failure, is essential if their support for the research program is to be maintained.

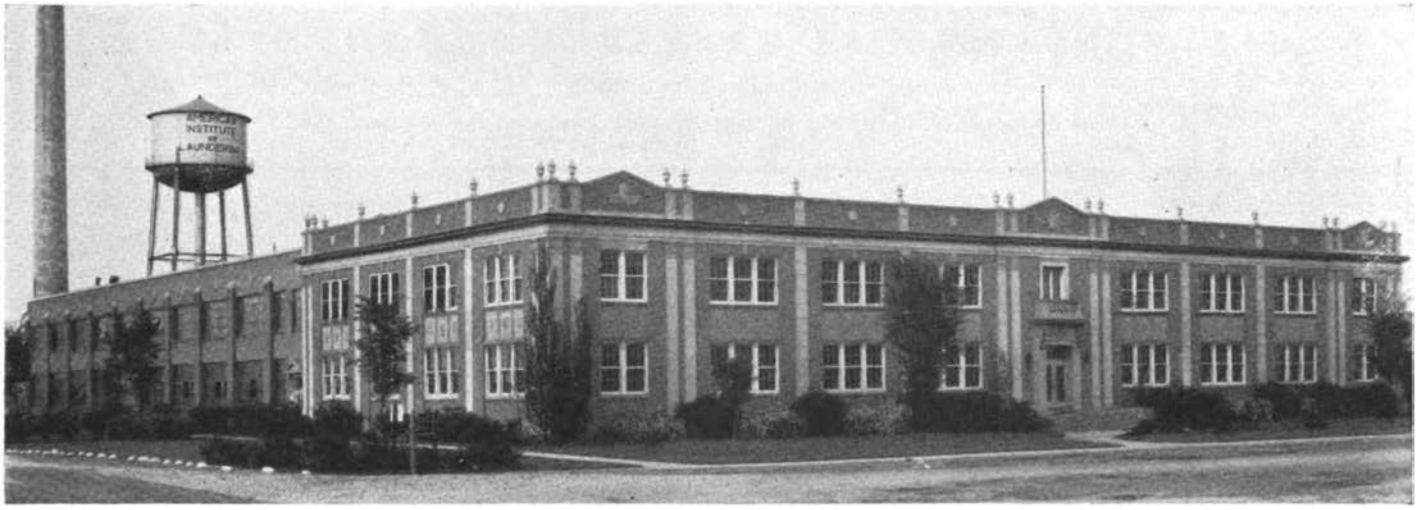

FIGURE 17.—Laboratories and Offices of the American Institute of Laundering, Joliet, Illinois

National Emergency

In any national emergency trade-association technical research facilities can be converted to Government use easily and immediately. Research committees, being already organized and functioning, can render immediate, competent service in making technical surveys of the industry or in assisting in the conversion of nonessential industries to the production of munitions and war materials generally. The trained personnel of laboratories in operation would be particularly valuable in undertaking special research along their specialized line, or along similar lines. The staff and facilities of trade-association chemical laboratories, if necessary, could easily be utilized in the small-scale production of special chemical products or medical preparations needed for war use. Engineering and other types of laboratories could be used likewise along their specialized lines. Inasmuch as trade-association research laboratories are, as a rule, not connected with any particular factory or manufacturing enterprise, their mobilization into emergency work would not have the effect of reducing industrial production.

Technical research by trade associations has become a great national asset. It is as yet inadequately developed. Potentially, the research facilities of trade associations are of major importance to national mobilization. In the event of national emergencies, facilities owned by production enterprises should be interfered with as little as possible in order that maximum production and expansion may take place. In trade-association laboratories may be found able scientists with efficient, trained assistants whose immediate work can, without permanent loss, be temporarily discontinued that their efforts may be devoted to the common cause. They may be made our first auxiliary line of technical defense.

In closing this discussion the author wishes to make it altogether clear that in mentioning or describing as examples the research work of a few associations, no derogation of the fine work of many others is intended. Only space limitations and lack of complete knowledge are responsible.

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SECTION II

5. FUNDAMENTAL RESEARCH IN INDUSTRY

By Charles M. A. Stine

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ABSTRACT

Fundamental research is a quest for facts about the properties and behavior of matter, without regard to a specific application of the facts discovered. Fundamental research in industry is a sound business policy because (1) it provides a basis for future processes and products; (2) it is a logical approach to the more difficult or complex "practical" problems; (3) it is an assurance of continued leadership in quality and economy of production.

In addition, there are several important secondary factors resulting from industrial fundamental research, namely: (1) Fundamental research creates consulting specialists within a company, readily accessible to those engaged in applied research; (2) it broadens and strengthens relations with university research; (3) it attracts to a company university graduates having distinct aptitude for research; (4) it provides an opportunity within a company for placing personnel who might otherwise be misfits.

In the du Pont Company each of the operating departments and subsidiaries has a research division. Many problems of interest to two or more operating departments, however, are handled by an independent central research department. The fundamental research staff is within the administration of the central research department.

The fundamental research staff of the du Pont Company now comprises about 45 men, including full-time group leaders and other supervisory personnel. The investment in research facilities is approximately $10,000 for each scientifically trained worker. The operating expense is approximately $7,000 to $8,000 annually for each scientifically trained worker.

Fundamental research should be undertaken only as a long-range effort, rather than on a year-to-year basis. Significant results seldom appear in a year's program. It is desirable, too, to assure personnel generous compensation and security of employment. For these reasons fundamental research in industry is somewhat limited to companies of considerable size, seasoned experience, sound financial condition, and demonstrated faith in research generally. But a small company may participate in fundamental research and profit from it, particularly by obtaining assistance outside its own organization.

The du Pont Company's program of fundamental research has been in operation 12 years. Substantial results have been achieved in the following lines of work: Giant molecules, or "superpolymers" (nylon); chemical engineering unit operations; organic synthesis, including studies of acetylene polymers resulting in neoprene chloroprene rubber; cellulose derivatives; catalyst studies; and pigments and particle size.

Although pioneering applied research may enlarge existing fields, fundamental research broadens the whole field of chemical industry, and from it flow new products and new processes. These new products exhibit not only the properties expected by their discoverer, but, as so frequently happens, new and unexpected properties which result in new uses not envisioned for it when the product was merely a dream in the mind of the inventor.

Introduction

Fundamental research and what may be termed "pioneering applied research" should be differentiated. The distinction is based principally upon the scope of the work and the extent to which it is limited by certain recognized practical objectives. In general, research undertaken upon some broad general subject, such as the structure of cellulose, belongs to the category of fundamental research.

On the other hand, if a company engaged in the production of textiles coated with cellulose derivatives, or in the manufacture of photographic film, or of other products utilizing derivatives of cellulose, undertakes research aimed at the development of new cellulose derivatives, in the hope of developing such derivatives as might exhibit useful properties fitting them for application in manufactured products, the work becomes pioneering applied research. After the discovery of a new cellulose derivative and the evaluation of its properties, the next step might be actually to manufacture it, whereupon the investigation assumes the complexion of ordinary applied research.

The investigation of monomolecular films by a producer of electrical equipment might be fundamental research, whereas the investigation of monomolecular films by an oil refiner engaged in the production of lubricants might be largely in the field of applied research. Thus, the classification of the research depends upon the character of the problem and the nature of the agency carrying on the investigation.

Reasons for Fundamental Research in Industry

Why fundamental research? The answer is clear; industry should learn today in order that it may be prepared for tomorrow. Thus, there is an implied monetary motive for fundamental research in industry. To put it another way, fundamental research in the technical laboratory is not a labor of love. It is sound business policy. It is a policy that should assure the payment of future dividends. More specifically, fundamental research in industry aids in achieving the following things:

(1) Fundamental research provides a basis for future processes and products. For example, a substantial proportion of the operations of a certain company is based on the raw material cellulose, and it is likely that the company will continue to use cellulose in large quantities every year. Consequently, such studies as "chemistry of cellulose," "particle size of cellulose derivatives," and "physical structure of cellulose derivatives" are a part of the fundamental research effort. It is believed that some of the discoveries being made inevitably will lead to new cellulose products.

(2) Fundamental research is a logical approach to the more difficult or complex "practical" problems, such as the design of equipment for chemical and physical processes. After a process has been carried through the laboratory stage, what then? Unless the process is conventional—which it rarely is—the steps which ensue comprise semiworks operation, followed by the design of a full-scale factory, all of which require such data as coefficients of heat transfer and empirical formulae for absorption and fluid flow. If the plant operates according to prediction, there is a general sigh of relief. While there is a body of knowledge called chemical engineering, there are many open spaces in that knowledge, as the designer of chemical factories will testify. Therefore, in the hope and belief that guesswork in plant design can be diminished, fundamental research in chemical engineering should embrace studies in fluid flow, distillation, absorption, crystallization and evaporation, heat transfer, and the like.

(3) Fundamental research assures continued leadership in quality and economy of production. Paint, for instance, is an old product, so old one might think there is not much room for improvement in quality. But research is destined to cause much more than continued improvement in present types of paint. New types of paint will be evolved. Significantly, a paint is judged partly by the way it fails; whether by chalking, cracking, blistering, etc. Short life—from 1 to 5 years—is an accepted quality. So, with these facts in mind, fundamental research especially on pigments is in progress in the paint industry. Such properties as particle size and size distribution are being studied, using the ultracentrifuge as a tool. Fundamental laws are being discovered, and these discoveries will permit a control of the optical properties of pigments. As a result, paints having vastly improved durability may be expected.

(4) Fundamental research creates specialists within a company, readily accessible for consultation with those engaged in applied research, or themselves to undertake applied research with assurance of a broader foundation than otherwise would have been laid. Experience indicates that the consulting function does not interfere seriously with the research function; on the contrary, contact between the two research groups is mutually beneficial. Or alternately, fundamental research may be an excellent prelude to pioneering applied research.

(5) Opportunity for fundamental research attracts to industry university graduates having marked aptitude for research. This is important, because in a large technical research organization, the recruiting of members for the junior technical staff is a major responsibility. The research results of tomorrow depend upon the quality of personnel employed today. Stated another way, the scientific prestige of a company is a major factor in attracting suitable men, and this prestige often rests on the company's reputation for fundamental attack.

Organization for Fundamental Research

In one company in which fundamental research has been practiced a number of years, each of the operating departments and subsidiaries has a research division. To that extent, research is decentralized. Many problems, however, especially those of pioneering applied research are of interest to two or more operating departments or for other reasons are handled most effectively by an independent research staff. Consequently, there is also a central research staff. The fundamental research staff appears most logically to be a part of the central research department and, in fact, is administered therein.

Actually, there is no sharp subdivision of organization, since certain individuals engaged in fundamental research report to supervisors who also have responsibility for pioneering applied research. This has proved quite satisfactory and ensures fraternity among the applied and fundamental groups. Any appearance of having set up an aristocracy of fundamental research is carefully avoided. All research is considered to be equally important to the company's welfare; similarly there is no inequality of status as between an employee engaged in an abstract study of the cellulose molecule and one trying to make better photographic film from that same cellulose.

The fundamental research staff of the company now comprises about 45 men, including the full-time group leaders and other supervisory personnel.

Cost of Research

In this same company, the investment in research facilities is approximately $10,000 for each scientifically trained worker, whether engaged in fundamental research or in applied research. This includes all capital facilities, such as land, buildings, and equipment. The operating expense is approximately $7,000 to $8,000 for each scientifically trained worker. This includes the worker's salary and his overhead—such items as rent (or the equivalent of rent), heat, light, power, supplies, insurance, clerical, and mechanical services, administration, and travel.

Conditions for Successful Fundamental Research

Everyone experienced in fundamental research knows it should be undertaken only as a long-range effort. Accordingly, a management should understand that, in all probability, significant results will not be forthcoming in a year's program. Fundamental research should be underwritten for a term of years, rather than on a year-to-year basis. One program in the writer's experience was underwritten initially for a term of 5 years, and when this term ended, the results were sufficiently tangible to warrant continued appropriations.

A second factor is the lines of work to be undertaken. "Lines of work" rather than "problems" are specified, because problems were not specified when the program was initiated. In one company, for example, there are a number of major lines of manufacture, and underlying these are cellulose chemistry, catalytic reactions, a group of organic syntheses, a group of inorganic syntheses, also certain physical phenomena, as for example, those related to paint manufacture.

Clearly, it is good policy to try unceasingly to improve existing products through applied research and to develop new products through pioneering applied research. Having organized applied research to the best advantage, the possible additional benefits to be secured by fundamental research should then be considered. Finally, if fundamental research is conducted on the broad lines underlying the various industries, facts that sooner or later will be valuable are most likely to be discovered.

A third factor is personnel. Individual ability is even more important in fundamental research than in applied research. Reaching a clearly defined objective in applied research is not difficult if proper supervision is provided. If this were not true, applied research would not have achieved virtually universal acceptance as an everyday business tool. Of course, someone has to supervise fundamental research. However, the supervisor's principal task is to contribute suggestions and constructive criticism, to see that working conditions are favorable, to inspire his men, and to maintain close touch with the progress of each group member. The success of the work is largely dependent upon securing for fundamental research the highest grade of men obtainable for each of the principal lines of work and then affording them a wide latitude.

It is desirable to compensate these men so generously that they will regard themselves as "career men" with a company. Once a man has demonstrated his ability for work in fundamental research, security of employment and fair compensation ought to be assured insofar as possible.

The foregoing considerations indicate at once why fundamental research in industry virtually is limited to companies of considerable size, seasoned experienced, sound financial condition, and demonstrated faith in research generally. To put it another way, no company should undertake fundamental research unless it is both willing and able to sustain it indefinitely, through depression as well as prosperity. In this connection, it should be pointed out that the lapse of time between the conception of an idea in fundamental research and its eventual emergence as an industrial process or product is rarely less than 6 to 10 years.

Results Achieved

Fundamental research is not new in industry. It has been practiced with marked success by the chemical industry on organic syntheses, catalysis, and polymerization; by the electrical industry on acoustics, surface films, and atom smashing; by the iron and steel industry on creep; by the paper industry on the properties of lignin. Even a gasket company has carried out basic research on the laws affecting leakage without having in mind specific commercial problems.

Indicative of the range of fundamental research in industry, the following examples are cited. These examples were contributed especially for inclusion in this report, as a result of the author's contact with a number of companies, the cooperation of which is hereby acknowledged.

American Cyanamid Company

Physical laboratory.—"A spectroscopic study of atomic arrangement and structure of organic compounds in the spectral range between 2,200–A and 120,000–A. New instruments and technique have been developed and a catalog of the spectral bands of molecular groupings is being compiled. Some very valuable applications, particularly in the analyses of unknown organic mixtures, have resulted."

Chemical laboratory.—"A comprehensive study of organic nitrogen compounds, particularly derivatives of cyanamid. This has resulted in the production of many new products, several of which are now commercially available in the class of organic bases, resin forming compounds and intermediates for pharmaceutical and dye production. Much new physical and chemical data relating to the properties of these complex compounds have been registered."

Biological laboratory.—"Organized research on the nature and behavior of globulin proteins leading to a better understanding of the complex constitution of serums. We are now able to produce certain antitoxins and toxoids free from certain side reactions when introduced into the human system, and with better understanding of the principles involved, the application is being extended rapidly to a wider range of these biologicals."

Bell Telephone Laboratories

Electron diffraction.—"Up until 1927, electrons were thought to be discrete particles; their mass and charge had been determined, and their behavior under all the more usual circumstances was known. Studies in Bell Telephone Laboratories, however, showed that electrons also have the character of waves. This was proved by projecting a stream of electrons against a nickel crystal. Instead of penetrating or being blocked by the nickel crystal, the electrons are diffracted, and leave the crystals at various angles from the line of the beam, much as a beam of light is diffracted when it falls on a fine mesh screen. This result was in conformity with certain theories developed shortly before, and has been one of the important factors in creating the 'new' physics that has come into prominence in recent years. Since this original work, the diffraction of electrons has proved a useful tool in studying the nature of material surfaces."

Electron emission.—"Studies have been carried on over a number of years to determine the fundamental

Figure 18.—High-Speed Motion Pictures of the Human Vocal Cords, Bell Telephone Laboratories, New York, New York

physical and chemical factors involved in emission of electrons from heated surfaces. The broad objective has been to improve the uniformity, efficiency, and life expectancy of vacuum tubes. At the time these studies were initiated, Wehnelt or oxide coated cathodes, were known but their behavior was erratic and their preparation difficult. As a result of extended researches, the principles involved in electron emission have been greatly clarified. The role of metallic barium in oxide coated cathodes is now understood from these studies, and this knowledge has facilitated the development of manufacturing processes for the production of more uniform and efficient tubes of longer life. Both the efficiency and life of vacuum tubes have been increased many fold as a result of these studies."

Corning Glass Works

Shrunk glass.—"The development of 'shrunk' glass might be taken as an instance of a commercial result of fundamental research in an industrial laboratory.

"It had been observed that prolonged heat treatment in the annealing region seriously affected the resistance of certain glasses to attack by water and chemical reagents. With no immediate practical application in view a study of the phenomenon was undertaken. After work extending over a period of years it was found that certain chemical compositions were particularly susceptible to heat treatment, the result of which appeared to be the separation of the glass into two phases, one consisting almost entirely of silica and the other of boric oxide, alkali, and other constituents. Extraction with acid then gave an article of the original size, microscopically porous and consisting of some 96 percent silica, which on firing contracted in volume about 35 percent and yet retained with remarkable fidelity its original shape.

"It has thus become possible to produce from a glass melted and worked by conventional methods ware which in its properties approaches fused quartz. The expansion-coefficient of the 'shrunk' glass, for instance, is 0.0000008 where that of fused quartz is 0.0000006. Electrical properties and resistance to chemical attack are also close to fused quartz.

"The glass is now on the market in the form of laboratory ware and in other special applications."

Eastman Kodak Company

Distillation in high vacua.—"A very typical example of the application of fundamental research is Dr. Hickman's process of distillation in high vacua, which resulted from a study of the design of vacuum gauges and pumps. This was undertaken originally as a purely fundamental research, without any particular application in view and has enabled us to design and build molecular stills and to carry on the commercial distillation of vitamins from fish oils in a subsidiary company formed for the purpose.

FIGURE 19.—Pure Research Division, Stamford Research Laboratories, American Cyanamid Company, Stamford, Connecticut

There are many other applications of this distillation process to the treatment of vegetable and animal oils, all of which are developing from Dr. Hickman's work on high vacua."

General Electric Company

High-pressure arc work.—"High-pressure arc work (electric discharges in high pressures of gas, up to 50,000 pounds per square inch) has taught us how to improve air circuit breakers so that an air circuit breaker may now be made as compact as an oil circuit breaker for the same service."

Hot filaments.—"At a time when X-ray tubes contained no filaments, researches on phenomena connected with hot filaments yielded the clew to a new type of X-ray tube, so superior to former types as completely to supersede them."

Monsanto Chemical Company

Ferric sulfate.—"Fundamental study of the system Fe_2O_3—SO_3—H_2O, out of which rose efficient manufacturing methods for ferric sulfate."

Synthetic resins from petroleum.—"Study of the reactions of olefins with diolefins and aromatics resulting in the development of resins from petroleum."

Organic phosphates.—"Study of the reactions of phosphoric anhydride with organic compounds resulting in the development of alkyl phosphates."

Standard Oil Development Company

Lubrication studies.—"In connection with a study of lubricating oil behavior it was found that a new synthetic material had the effect of reducing the pour point of lubricating oils. Manufacture of this material was started within the company and it is now sold in the form of an oil solution as 'Paraflow.' The production of this material has been a quite successful commercial enterprise."

Polymerization studies.—"In connection with examination of the constitution of petroleum fractions, it was found that the hydrogenated polymerization product obtained from treating refinery C4 cut, with moderately strong sulfuric acid, at essentially room temperature contained octenes other than 2,2,4-tri-methyl pentane, normally known as iso-octane. Up to that time it had been felt that the only product of the reaction was the polymerization of isobutylene to di-isobutylene which would be converted to 2,2,4-trimethyl pentane on hydrogenation. Discovery of the presence of other octenes stimulated work on the modification of the polymerization process which led to the development, so far as the Standard Oil Development Company is concerned, of the 'hot acid' process for production of mixed octenes by polymerization of isobutylene with normal butylenes. Development of this process more than doubled the supply of aviation gasoline blending agents that could be obtained from refinery C4 fractions as compared with the earlier 'cold acid' process. This work made possible the production of high octane number blending agents for aviation gasoline on a scale large enough to warrant wide application."

United States Rubber Company

Research on latex.—"Shortly after the close of the last world war the United States Rubber Company began importing latex from its plantations. It appeared immediately that latex could be used for a number of purposes, including the direct manufacture of rubber goods, which up to that time had been made from the coagulated and dried rubber shipped from the East.

"In order to develop such processes and operate them on a satisfactory basis a large amount of fundamental research work was carried on. Among other matters, studies were made of the viscosity of latex in relation to its concentration, pH, and the effect of nonrubber materials, including compounding ingredients.

"As a result of this work we are now able to make reproducible latex compositions and to maintain the properties of these compositions over considerable periods of time."

Some of the practical applications of this work are the following:

Latex thread (*Lastex*).—This is widely used in the manufacture of elastic fabrics and garments.

Latex wire.—This product is superior to wire insulated by the older methods using dry rubber, in that the wall thickness is more uniform and the dielectric properties of the rubber are superior. As a result, wires made by this method have a smaller over-all diameter for the same service than wires made by the older method.

Latex foam sponge.—This material is coming into wide use for cushions for automobiles, furniture, and mattresses.

Westinghouse Electric & Manufacturing Company

Electric discharge phenomena in gases.—"In the electrical industry, there has been considerable fundamental work in the ionization, conduction and deionization of gases and this fundamental work has led to valuable commercial products such as lightning arresters and circuit breakers.

"It might be pointed out also that the early fundamental work, partly in industry and partly in the universities, on conduction in gases at reduced pressures has resulted in quite a long trail of useful products such as X-ray tubes, mercury vapor lights, mercury rectifiers, radio and industrial tubes, fluorescent lights, photocells, sterilizing lights, etc."

General Motors Corporation

Improvement of antiknock quality of fuels.—"This research program was started in an effort to eliminate detonation in gasoline engines. Detonation, or 'knocking,' results in low economy and prevents the use of high compression ratios with consequent performance increases. The General Motors Research Laboratories found that the addition of tetraethyl lead to gasoline raised its antiknock value so that engineers could use the advantages of high compression in engine design. To use tetraethyl lead without causing lead deposits inside the engine, it must be mixed with a bromine derivative, ethylene-dibromide."

Improvement in quality of gasoline.—"The General Motors Research Laboratories engineers, cooperating with the oil companies, have about doubled the yield of gasoline from crude oil. The inherent antiknock value of gasoline has been greatly increased and, in addition, the chemists have found many ways to use petroleum as a raw material."

Fuel economies.—"In 1939 about 75 percent of the gasoline sold in this country contained ethyl fluid. The annual gasoline bill of the United States is about 4 billion dollars. Engine improvements made possible by better antiknock fuels have about doubled the power and economy without increasing the size of the engine. Refiners now sell better gasoline at a lower cost to the public and in addition have found ways to make alcohols, solvents, acetylene, plastics, resins, artificial rubber, and a host of other things, using petroleum as the base material. No quantitive measurement can be applied to the over-all benefits of fuel research, but they may be largely credited to the forward research policy of General Motors."

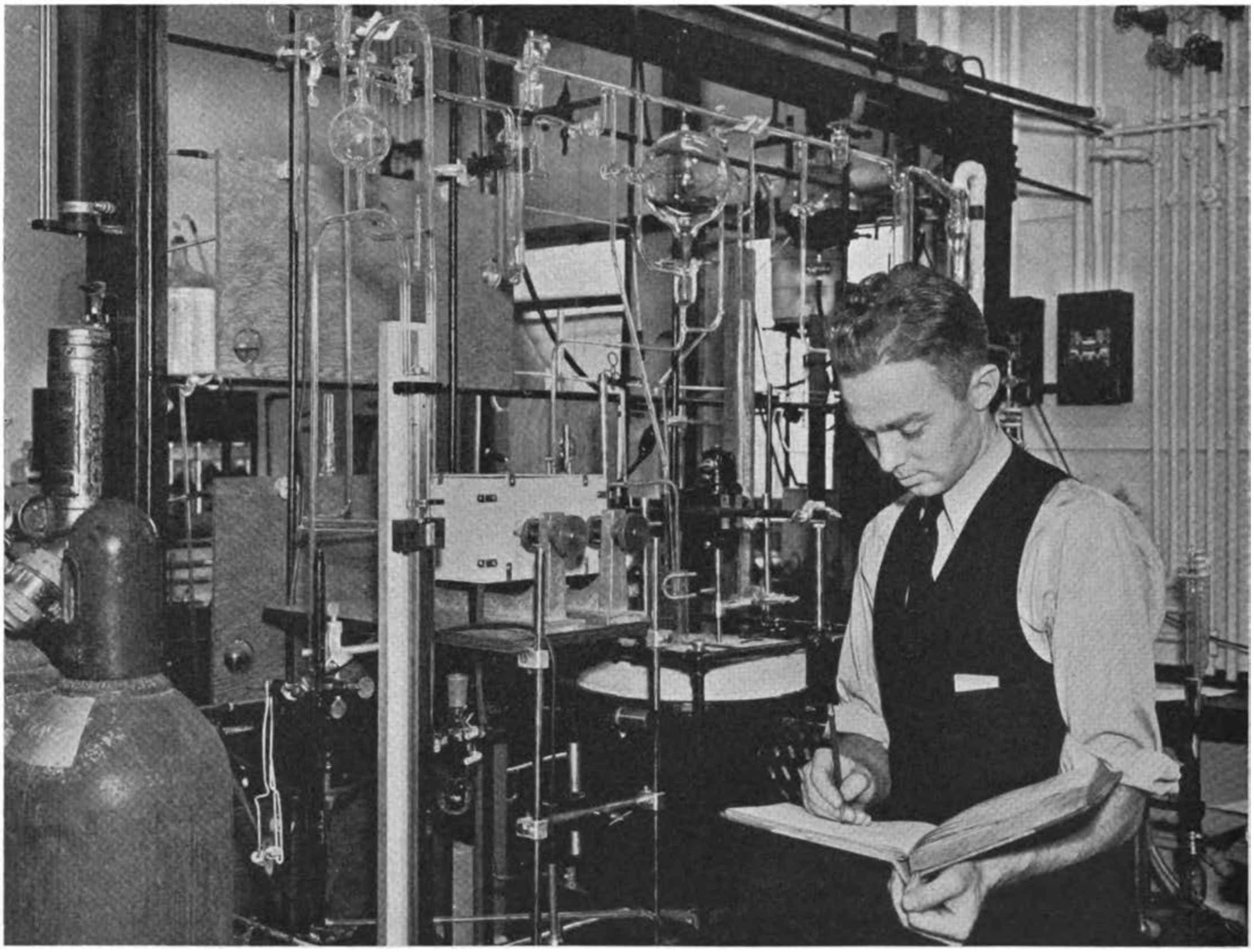

FIGURE 20.—Fundamental Research in Reaction Kinetics, Emeryville Laboratories, Shell Development Company, Emeryville, California

E. I. du Pont de Nemours & Company

Nylon.—In the 12 years of operation of fundamental research, substantial contributions have been made to the company's progress, as indicated by the following description of the nylon development:

The first study undertaken in fundamental research program was directed to a better understanding of how and why certain molecules unite to form giant molecules, such as those found in rubber, cellulose, and resins. Chemists have long been vitally interested in giant molecules, or "superpolymers," and in learning everything possible about the mechanism of polymerization.

Out of the study of polymerization begun in 1928, fundamental information of much importance was developed and was made public in the form of scientific papers. It was demonstrated, for example, that certain small molecules could be made to unite in such a way as to form giant molecules of great length, known as linear superpolymers.

However, after this fundamental research had been under way for about 2 years, it was noted that the molten polymer could be drawn out in the form of a long fiber, somewhat like that of silk, and that, even after the fiber was cold, it could be further drawn to several times its original length.

While this original fiber was not very strong or elastic and was softened by hot water, it, nevertheless, suggested the possibility that some related type of superpolymer might give fibers which would possess the characteristics desired for use in textiles. Further research was accordingly directed to the synthesis of a superpolymer from which strong, elastic, and water-resistant fibers would be drawn or spun.

Practical research directed to the synthesis of a superpolymer from which fibers could be drawn suitable for textile purposes did not bear immediate fruit. Numerous superpolymers were synthesized. Some of the resulting fibers were deficient in strength and elasticity, while, others, although sufficiently strong and elastic, softened at quite low temperatures, or were sensitive to water. They did not possess the properties required of a textile fiber.

Finally a superpolymer of a different type was prepared, a polyamide, from which fibers spun by hand were found to possess such characteristics as to warrant extraordinary efforts to bring the development to commercial success. Much work was yet to be done, however, between that day when the first polyamide fiber was extruded through an improvised spinneret made from a hypodermic needle, and the announce-

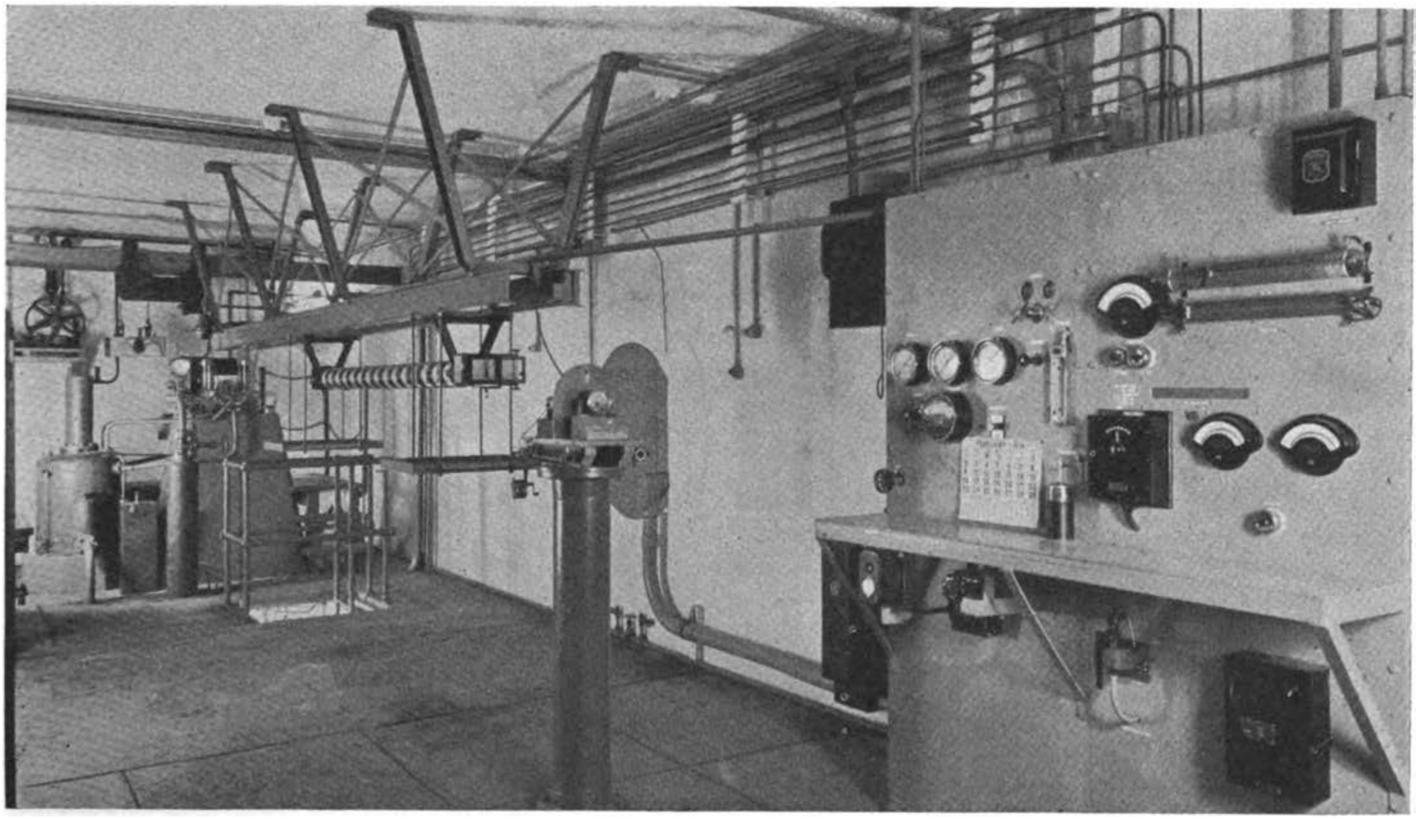

FIGURE 21.—Ultracentrifuge for Determination of Molecular Weights of Colloidal Materials Such as Proteins, Cellulose and Rubber, Experimental Station of E. I. du Pont de Nemours and Company, Wilmington, Delaware

ment of nylon several years later. Many different polyamides had to be synthesized before superpolymers having the desired characteristics were found; it was then necessary to investigate sources of raw materials for the intermediates needed in making these superpolymers, and to devise practicable processes for making the intermediates.

Late in 1938, there was announced the development of a group of new synthetic superpolymers from which, among other possible applications, textile fibers could be spun surpassing in strength and elasticity any previously known textile fiber, whether cotton, linen, wool, silk, or rayon. This new family of materials was named nylon.

Fundamental Research by Small Companies

The small industrial organization has been variously defined. Certainly with respect to the largest companies, one whose net worth is 1 million dollars would be considered small. Such an organization on the average would have a gross income of 1 million dollars annually and could support a research staff of about 5 scientifically trained personnel. On the other hand, a company whose net worth is 5 million dollars ceases to be small (if engaged in manufacturing) and might be termed medium-sized. It could support a research staff of 20 scientifically trained personnel.

The question is, What can a company do—in this category of less than 20 research men—in the field of fundamental research? Its managers probably feel that its resources should be conserved for projects that promise relatively definite and prompt return; that fundamental research should not be undertaken unless there is reasonable assurance of financial support over a period of years; and that the successful pursuit of fundamental research requires a staff possessing widely diversified, highly specialized talents. Finally, they may feel that fundamental research is a variety of "white man's burden," to be borne by the universities, research foundations, and large industrial companies.

Such reasoning does not, in the writer's opinion, close the case, as there are ways by which a small company may participate in fundamental research and profit therefrom. For example, it may sponsor a project in a university, or establish a fellowship at an endowed research institute at which admirable staff and equipment are available for the small as well as the large organization. It may participate in trade association research or in cooperative group research. It may retain a firm of competent research consultants.

Fundamental Research and Foreign Affairs

In the light of world politics as this is written, the importance of maintaining and expanding research activities in America becomes particularly clear. Our ability as a Nation to hold and develop foreign trade and to provide adequate defenses will depend in no small degree upon our research activities, including those of the most fundamental character.

Twenty-five years ago Germany was supreme in dyes, pharmaceuticals, and nitrogen fixation, simply because she had built efficient industries upon a broad base of fundamental research that dated back 10, 15, and 25 years. No imagination is required to appreciate what this supremacy meant in her world commerce and in preparedness for war.

Fortunately, our woeful state of chemical insufficiency in 1914 is one lesson America took to heart. And, if we are to survive as a democracy in a world seething with predatory powers, then our defenses must be made secure, literally down to the last atom. Whether or not we relish the idea, our leadership in science must not be relinquished if we are to be invincible in the arts of war as well as in the bloodless but nonetheless vital struggles of world commerce.

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SECTION II

6. CAREERS IN RESEARCH

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ABSTRACT

Success in industrial research depends primarily on human effort, therefore, a discussion of the qualifications of industrial research workers is important. It is believed that a discussion of this subject from the standpoint of the individual will be of interest to the universities, to employers, and in particular to prospective research workers. The report is intended to state some of the results of experience, and in order to make it representative it has been reviewed by a large number of research directors, whose suggestions have, as far as possible, been included.

A number of qualifications are discussed, with explanations as to why they are important. Some of these qualifications are inherent; others may be acquired by training. It is emphasized that no attempt is made to state the degree to which these various qualifications are necessary. The field of research is so broad that it is not possible to draw specifications for any standard type of individual. If it were possible, it would not be desirable, because different types of work require different types of ability.

Formal training of one kind or another is practically a mandatory requirement for one who hopes to become proficient as a research worker. It is achieved usually with the aid of a properly organized and equipped university. Emphasis should be put on the broad fundamentals of the chosen field rather than on specialization.

The importance of mathematics in connection with a scientific training is discussed.

Training in oral and written presentation of facts is generally held to be of extreme importance to the industrial research worker.

As to duration of training, it is the consensus of opinion that for a lifetime career in research, training equivalent to that required for the degree of doctor of philosophy is highly desirable. On the other hand, for development work or for work which is regarded as a training for some other field of industrial activity, a shorter period of training may be adequate. Graduate work should train a man in research methods. One of the most valuable features of graduate training may be the close association of the graduate student with a brilliant leader in science.

The relation of academic standing to success in industrial research is discussed, with the conclusion that while success cannot be predicted on the basis of academic standing, it is generally believed that to succeed, a student should be in the upper half or even in the upper fourth of his class. It is also agreed that good academic standing is no substitute for other qualities, and is in itself no guarantee of success.

In the selection of a position it is desirable for the applicant to secure as much information as possible regarding the requirements so that he may determine whether his qualifications and aptitudes are suited. It is pointed out that the research history of the company is also a matter of interest.

Management policies, organization, and procedures are discussed, with particular reference to how these relate to the individual. Specific topics discussed are the acquisition of experience, evaluation and utilization of ideas, leadership, ability to complete as well as start work, planning, essentials and nonessentials, and execution.

It is pointed out that work in a research laboratory may provide training for positions in other parts of the company.

As to compensation, it is believed that the scientific men in industry fare as well, on the average, as men of comparable age, experience, and ability in other industrial activities. In addition, there are a number of other important compensations. A low-paid apprenticeship is ordinarily not required. A man who possesses the qualifications of a scientist will probably be happiest if he is doing this type of work, also, he will derive satisfaction from the fact that his work may be of great and lasting importance. Most industrial laboratories permit workers to publish the results of their work where such publication will not be prejudicial to the interests of the company.

It is generally agreed that industrial research in this country will experience a large growth.

Introduction

The resources of the United States for industrial research are measured by the personnel available to carry on this work. This statement may seem an exaggeration because there is a tendency to regard the achievements of industrial research as resulting from physical equipment such as laboratories and apparatus. While these are essential, they are of little use without the proper personnel. In the last analysis the achievements of industrial research are the results of human effort. For this reason it is highly important to consider carefully the question of scientific personnel—what kinds of men are most suited to industrial research, and how they should be trained.

While a number of previous writers have discussed the qualifications required for research work, this has been done largely from the standpoint of informing the prospective employer as to what sort of men he should seek. Furthermore, in many cases emphasis has been placed on one or two qualifications. It is therefore believed that a study of this subject should be of value. One possible benefit of such a discussion will be that prospective research workers will have a clearer idea of the desirable qualifications so that they will be better able to prepare themselves for a career in research. It may also attract men who would be admirably suited for industrial research but who do not realize that they possess the proper qualifications.

It is hoped that this discussion will be of use to the educational institutions of the country, which have the responsibility of training the men who man our research laboratories. A fuller understanding of these problems should assist the universities to select and encourage men who have the necessary qualifications, to a considerable degree at least, and to train them.

It is not intended that this report should be taken as a homily addressed to young men about to engage in a career. The purpose is to state some of the results of experience and not to pronounce dogma. Suggestions are made on those subjects where experience has shown that improvement is possible by conscious effort.

Great pains have been taken to make this report representative. It was prepared in cooperation with research directors of companies employing a large proportion of the industrial research personnel of the country, and their criticisms and modifications have, as far as possible, been adopted. Where diverse views are held, an attempt has been made to include these.

A research director who has reviewed this report says:

> In industrial research there is a great deal of research activity which I classify as applied research that is carried on in close cooperation with mill operations and is, in effect, more in the form of development work in mill operations making use of the results of intensive, more fundamental laboratory effort. I think this type of work is quite often overlooked and yet I classify it quite definitely as research. It is perhaps what might have been called in older days, Yankee intuition or Yankee cleverness applied to mill problems. In larger organizations which can finance large research laboratories and also large development laboratories, there is opportunity to carry the results of fundamental research through rather large scale operations in a development laboratory, but with smaller organizations it is necessary to make the jump sometimes rather drastically from small scale "test-tube" experiments to mill operation, and this jump takes a lot of courage and careful application of fundamental knowledge combined with knowledge gained from practical experience together with a good measure of common sense and intuition.

Qualifications for a Career in Research

The field of industrial research is so broad and diverse that there is no standard type of individual worker therein for whom specifications can be drawn. It is possible, however, to state and explain a number of desirable qualifications, some of which have as their basis natural aptitude, while others may be acquired by training. It is not, in most cases, possible or desirable to make any definite statement as to the degree or extent to which these qualifications are present, and the degree to which they are present is probably not the same for any two individuals. One reason for this is that we lack the means to measure and evaluate these qualities. Another reason is that the field of research is so broad that various qualities are desirable, in varying degree, for different kinds of work. This point will be discussed in more detail in the summaries which follow the sections on qualifications and training.

Personal Qualifications

Intellectual integrity.—This is one quality that should be possessed without any qualifications as to degree. It is the sine qua non of the scientist. By this term we mean not only the willingness but also the ability to recognize the truth. It is vitally important that a man who plans to do research work be capable of distinguishing truth from untruth, and of being able to differentiate that which may be true from that which has been verified. In the words of T. H. Huxley—"The man of science has learned to believe in justification, not by faith but by verification." Possession of this quality implies the ability of self-criticism, and an objective rather than a subjective attitude toward facts.

Scientific curiosity and creative urge.—These have been the motive forces behind many of our great scientific advances. The scientist who possesses a high degree of scientific curiosity is prepared to seize upon the most meager clues. Small clues have sometimes led to far-reaching and unexpected results. For example, argon was discovered as a result of an observation that atmospheric nitrogen prepared from the air had a slightly greater density than nitrogen prepared by chemical means. A high degree of scientific curiosity is one of the sources of that driving energy which is so essential to creative work.

Enthusiasm and receptiveness to new ideas.—These qualities, which are closely allied, are matters of the spirit, and have characterized all great scientists. The man who lacks them will find it difficult to succeed in research and, in most cases, should be encouraged to adopt some other calling. On this type of individual an important research executive says:

> In selecting and dealing with research and development men for a number of years I have come to recognize a type which seem to me disqualifies them, no matter how well trained they may be or how promising they may otherwise appear. This type is the man who always seems to have a *negative reaction* to everything which is suggested. When he concentrates at all it is to bring his entire mental machinery into action on the negative instead of the constructive side of a proposal. He uses up all of the time of his directors and associates in an attempt to convince them that the thing won't work. He spends ten times as much time trying to prove that it will not work as would be required to try the experiment. He drags his feet in the sand on every program with which he is connected.

Ambition and diligence.—These characteristics are standard practical virtues, but we use the terms here in a somewhat special sense. The term "ambition" implies particularly the intense desire to accomplish well the task in hand, "a worthy eagerness to accomplish something great and good." Diligence does not mean merely keeping busy, but the application of one's whole attention to the task. The exercise of diligence requires mental as well as physical activity, both focused on essentials. For success in research, there is no substitute for hard work. The men who succeed pay little attention to the clock or the calendar so far as working hours are concerned. One research director writes:

> The developments which advanced American industry to its present point were not made by men who worked 2,000 hours a year (including holidays), out of a total of 8,760 hours available. It would be interesting to know how many hours and for how many years the directors of industrial research worked (and probably still work) at their jobs during the years in which they accomplished the results which put them and their industries where they are today.

Ability to cooperate.—Writers on the qualifications for industrial research personnel have laid particular emphasis on the need for cooperativeness. Cooperation between individuals in the research organization and between the research organization and other units or divisions of the company is essential. In industrial research work, as in many other fields of endeavor, it is difficult if not impossible for an individual to succeed by his own efforts. The research worker frequently has to seek the advice and assistance of his fellows who have had experience that may be useful to him, and he must be prepared to reciprocate in turn. It is also necessary to secure the assistance of persons and facilities in other parts of the company, and this must be done through a spirit of cooperation. Cooperativeness should not be negative, but positive and rational. It should not take the form of mere acquiescence as that is of little value to the organization and is harmful to the individual. Positive and rational cooperativeness preserves the independence of the individual and is beneficial to both parties. It is in this sense that we use the term.

Perseverance.—The will to succeed will prevent the scientific worker from being too easily discouraged or deterred from his work by unsuccessful results or by the pessimistic views of others. This quality should be exercised with judgment. Much useless effort has been expended in the past by workers who were too persevering, too optimistic, too slow to face the facts, or who even refused to face the facts. A person with these qualities properly balanced will know when to persevere along a fixed line of endeavor and when to persevere toward the same objective but by a new route where results indicate that a change in plans is necessary.

Courage and self-confidence.—Scientific research requires courage and self-confidence. These qualities will prevent the investigator from being deterred from entering new fields because they are new and particularly because others may have failed in similar attempts. Courage and self-confidence will enable a person who possesses these qualities to form and hold his own conclusions as long as facts justify doing so. He will hold these conclusions even in the face of opposition which is based on prejudice. He will also have the courage to give up his opinions when facts no longer justify their retention.

Judgment.—Judgment has been defined as "the power of arriving at a wise decision or conclusion on the basis of indications and probabilities, when the facts are not clearly ascertained." This meaning of the term is here relevant. In technical work, some of the necessary facts are usually understood and others are not. A man of sound judgment will take both the known and the unknown into consideration and will make a particular effort to include everything that may be important. He will not waste his time on nonessentials. He will also have a proper regard for the relationship between the advantages and disadvantages which may result respectively from a right or a wrong decision. The ability to observe, associate, compare, and analyze forms the very foundation of research work, whether academic or industrial.

Imagination and ingenuity.—These qualities form the basis for the more creative types of research that produce inventions relating to new products and new processes. These result much more frequently from the exercise of imagination and ingenuity than from accidental discovery. In work of this type these qualities are regarded as essentials. Resourcefulness in experimentation is an important practical embodiment of these qualities.

Practicality.—This characteristic is one which, according to some nontechnical critics, scientific men frequently lack. This discussion is limited to a definition of our meaning of this term and the extent to which it is important. It is desirable for an industrial research worker to be practical in the sense of recognizing as important not only the purely scientific aspects of his work but also its practical consequences. These include the cost of doing the work and the commercial effectiveness of the results. While, in some instances, useful work may be done by persons who disregard these considerations entirely, in most cases it is desirable that the research worker be practical to this extent at least. One measure of practicality is the pertinence and applicability of results.

Common sense.—Common sense is a quality just as essential in research work as in other walks of life. The scientific man who has common sense and exercises it will give proper weight to the opinions of others even though these are not expressed in technical terms. He will be tolerant and will be more interested in the spirit of things than in the letter. In a discussion or argument he will regard his point as being won when an agreement has been reached on essentials.

Personality.—The scientist frequently is supposed to be deficient in personality. It is not our purpose at this time to argue that question, but it should be pointed out that a good personality is a distinct asset to the industrial research worker. A tactful personality will assist the individual to secure the cooperation of others, which is a matter of great importance in industrial work.

The qualities above mentioned are not substitutes for technical ability nor for other important attributes, but they help to make those other qualities effective. It should be stated here that there is considerable difference of opinion as to the amount of emphasis that should be placed on personality. There are many instances of men who have made a great success in research, and in other walks of life, who, in the opinion of their fellows have not possessed a normal personality. Some organizations insist on a pleasing personality—others say that it is of minor importance.

Training

For a career in industrial research sound training in one of the sciences and its related subjects, in research methods, and in certain nonscientific subjects, is generally held to be essential. Industrial research laboratories are for the most part staffed with men who have had such training. Also, whether this ability is derived from training or otherwise, an industrial research man should know how to work.

The first scientists in industry were, in many cases, self-trained or had received only rudimentary training from an educational institution. As manufacturing technique has become more precise as a result of competition and scientific advances, the training requirements for industrial scientists have become more exacting. Therefore, definite and comprehensive scientific training is, in practically all cases, necessary for one who aspires to a career in industrial research of the type with which this report is concerned.

We are not considering here those who are primarily inventors. There are innumerable instances of brilliant inventions which were made by persons having little or no formal training. Genius of this type is recognized and its value fully appreciated, but research work requires considerable organized knowledge of the facts, principles, and methods of science, and of their application. This knowledge can best be obtained at a properly organized and equipped university. It is not germane to propose curricula, but rather to indicate the consensus of opinion as to what a man who has had graduate training in science should know and be able to do when he leaves the university. The discussion includes not only scientific training, but also certain types of nonscientific training which are considered to be particularly useful.

Scientific training.—The basis of a satisfactory training for industrial research is a thorough grasp of the fundamentals of the chosen science. The term "fundamentals" as used herein may require further definition. By it we mean those classical principles which have been the basis of a great expansion of our scientific knowledge, with the emphasis on the applicability of the principle rather than on its philosophical significance.

A thorough grasp of the fundamentals also implies a working knowledge of them. There should be a recognition of how these principles may be involved in any new problem or in the explanation of new phenomena. There should also be an understanding of how to apply these principles to the solution of the problem and how to carry out this application in the laboratory.

The head of the department of chemistry in one of our most important universities made the following comment on these observations—

> Insistence on a thorough working knowledge of fundamental principles is entirely sound but insufficiently appreciated. The route to such a knowledge is through the substitution of problem solving courses and recitations instead of the descriptive courses which serve too often to mislead the student into believing he has attained comprehension when he has merely acquired a little specialized scientific jargon.
>
> The graduate research should also be a "pure" science subject for the reason that the methods and technique of pure science

> are the models which all practical applications follow more or less closely. There is also the added reason that science is advancing incomparably more rapidly today than it was twenty years ago and the youth who is not to be scientifically outmoded in a decade must be prepared the better to follow the advances of science per se.

One of the commonest criticisms of graduate students who apply for positions in industrial research is that they are weak in their grasp of these fundamentals and lack a working knowledge of them. A broad training with particular emphasis on these classical fundamentals is more desirable than a highly specialized training in some one technique, the utility of which may be limited. It is also of far more value for research work than a training in the specific industrial applications of science.

Related sciences: Scientific training for industrial research must include education in sciences closely related to the specialty chosen. While the greatest amount of emphasis should be placed on the particular branch of science selected for specialization general familiarity with related fields is often of considerable value. For example, chemists, particularly the physical chemists, should have considerable familiarity with physics, and physicists, with chemistry. While these related sciences are usually required, their usefulness in later work particularly in borderline fields may not always be recognized at the time the courses are taken. On this point one research director remarks that a knowledge of related sciences is particularly important for a man who works in a comparatively small organization which has a wide field of problems.

Mathematics: A training for industrial research work should give due attention to mathematics. An understanding of this subject is not only necessary for an understanding of physical sciences, but in recent years mathematics in the form of statistical analysis has been applied to a considerable extent in the planning of experiments, in the analysis of experimental data, and in the control of production. On this point a prominent professor of science says:

> The discipline of mathematics is much too long delayed in public schools. In England and France a child is well grounded in geometry, algebra, and trigonometry at the age of sixteen, fully two years earlier than here. The subject is also one of the best as a partial means of differentiating between levels of students.

Nonscientific training.—Science students tend to shun courses intended to cultivate facility in the written and oral presentation of facts. This may be because they are more interested in substance than in form. For several reasons, it is particularly important for the scientific man to be able to write and speak clearly and effectively. Research work requires more writing than other fields of industrial work. The subject matter of the work is such that its clear presentation is frequently a matter of some difficulty. Before the results of research work can be used, they must be understood and appreciated by others. Therefore, instruction in oral and written presentation should be regarded as a most important part of training for research work. In addition, the habit of taking pains in writing and speaking should be cultivated. "Easy writing makes hard reading." Knowledge of cognate subjects is essential.

Social contacts.—Extra curricula activities also have their place in the training schedule. Social contacts, for example, may serve a useful purpose. The time is past, if indeed it ever existed, when there was any reason for the scientist to look and act differently from his fellow men. The prospective worker in industrial research may properly regard social contacts as part of his training. These can do much to develop a satisfactory personality and an understanding of human nature, which are so important in cooperative work.

Duration of training.—Opinions differ as to the proper duration of training for a scientist who desires to enter an industrial research laboratory. There are numerous instances of men who have achieved great success in industrial research with little or no graduate training. In certain types of development work a bachelor's or master's training is held by some to be sufficient or even preferable. This is particularly true for those men who desire to work in an industrial research laboratory in preparation for a career in some other activity.

For a lifetime career in research, and particularly for work in fundamental research, the training required for a doctor's degree is believed desirable by most of the research directors who discussed this section of the report. In some cases, particularly for fundamental research, post-doctorate training is desirable.

Postgraduate work should give the student training in research method, and should develop the research attitude. One commentator remarks, "It is not so much an opportunity to specialize in a chosen subject as a chance to develop the technique and capacity for specializing in any research problem which may later be encountered."

Postgraduate work permits a relatively informal association of the student with the research professor who has demonstrated his research ability. It is through this association that the student's faculties for attacking research problems are developed. In fact, the belief is widely held that the most important training the graduate student receives is obtained in this way. The history of science from its earliest beginnings offers many examples of brilliant teachers who have produced brilliant students. One research director states:

> I agree that the great value of post-graduate training is in the association with the progress of work and thought of able leaders. By corollary, post-graduate work in a school which is simply filling out the gaps in an already established programme where

no new conceptions or creative thought is evident, is not of great value. In that event an industrial research laboratory is likely to prove more dynamic and provide better training.

Relation of academic standing to success in industrial research.—There is no general rule by means of which success in industrial research can be predicted on the basis of academic standing. Academic standing tends to measure the student's ability to study, to understand, and temporarily to remember, and is silent on the highly important question of creative ability, and on other qualifications. Another reason for this discrepancy is that the term "industrial research" is quite elastic and the personnel requirements differ between organizations.

This subject was discussed by a number of research directors. It was generally believed that to succeed in research a student should be in the upper half or even upper fourth of his class. Some laboratories have academic standards controlling the employment of new men, particularly men who have received the bachelor's degree. In several cases it was believed that the fact that a man was permitted to work for a graduate degree was a sufficient evidence of proficiency in studies. But there was general agreement that, although a good academic standing is desirable, or in some cases essential, it is no substitute for other essential qualities, and is in itself no guarantee of success.

Résumé of qualifications and training.—In the preceding pages we have discussed the various qualifications including training, which are believed to be important for a successful career in industrial research. The list is formidable but without minimizing the importance of these attributes it should be realized that they are important in varying degrees. Just which ones of them are most important in any given case depends on the nature of the work and type of organization. For fundamental research work more emphasis will probably be placed on those qualities and attainments which are usually associated with purely scientific work, and less on such qualities as personality, cooperativeness, practicality, and common sense. On the other hand, problems of a development type, such as the perfection of a new process, may emphasize these qualities, and demand less in the way of scientific curiosity, imagination, and an intensive training in pure science. In other words a paragon is not required for industrial research.

This summary is written as a result of studying a large number of suggestions from research directors who have read the foregoing section. As far as possible, these suggestions have been included in the final revision of the section. The replies indicated, however, a considerable diversity of opinion as to the relative importance of certain qualities, and this diversity exists largely because the inquiry embraced such a great variety of industries whose research activities cover a wide range of problems and responsibilities.

Selection of a Position

A candidate for a position should secure as much information as possible about exactly the qualifications required and should compare them with his own. The applicant will probably be on the safest ground if he secures a position that requires the training in which he specialized. While there are many notable exceptions, it is generally true that the best training, for example for organic chemical research, is specialization in organic chemistry.

If the candidate feels that he has a special aptitude for some particular type of work, he will do well to consider this as a desirable, although perhaps not an essential factor in selecting a position. For example, a man who much prefers to do fundamental research may find it worth his while to secure a position of this type in an industrial laboratory. Most large laboratories carry on work of this sort though only a portion of the staff is devoted to it.

The applicant should consider a number of other points relating to the particular organization with which he may become associated. The matter of financial terms is only one of these factors. He should also consider the record of the company and of the industry. Industries and companies which are well established and which have demonstrated that research is profitable to them, offer considerable promise from the standpoint of stability. In such cases the probabilities are that the work will be thoroughly organized, and that for the first few years, at least, the new employee will have considerable assistance in the way of training from those who have experience in the technical phases of the business.

The situation is somewhat different with respect to industries or organizations wherein research is fairly new. In these, while a field for research will probably exist, the course is not so well charted. Matters that have been in the art or handicraft stage will need to be reduced sooner or later to technical terms. Policies for carrying on technical work will not be so definitely established. In general, a position of this sort will offer considerable opportunities to the right men since they will be among the first to enter a new field.

Both types of work have advantages and disadvantages, and it is not the purpose here to recommend either in preference to the other, but merely to point out the difference that may exist and of which the prospective research worker should take account.

He should consider the record of his prospective employer from the standpoint of the ability of the organization to utilize the results of research, since no industrial research organization which is unable to get its results into commercial use can be regarded as successful.

The candidate should give consideration to the type of staff the prospective employer already has in order to determine how his qualifications and methods of working would fit into the organization.

In most organizations great emphasis is placed on the careful selection of technical personnel. The technical men are usually selected by the heads of the research organization, and in practically all cases a personal interview is involved. This may give the candidate an opportunity to secure information on some of the points we have discussed, and he should regard this interview as of equal interest to himself and to his prospective employer. It gives an opportunity for each party to become acquainted with the other. He should not hesitate to answer fully any questions, whether personal or technical, and should not hesitate to ask questions.

In some cases the interview may develop into a technical discussion which may appear to the candidate to be suspiciously close to an examination. In most cases these discussions are not carried on to reveal deficiencies in the candidate's knowledge. The purpose is rather to ascertain the lines of work for which the candidate is best suited.

Careers in Research

Organization

In this section we shall discuss the research organization from the standpoint of the individual.

There is no standard form of research organization. The variety of the work, its changing character, and the fact that research work depends on a peculiar combination of individual yet cooperative creative effort, make it unwise to attempt to apply any standardized form of organization.

One of the objectives of organization in a research laboratory is to augment the efficiency of the individual worker with the knowledge and experience of others who in most cases have had more experience in some phases of the work. The young man entering a research organization may have knowledge of the newer developments in science which the older men do not have; they in turn have a considerable amount of knowledge regarding the problems to be solved, and have had experience in applying science to their solution. The young man will probably be assigned to a group headed by an older, more experienced man who will direct his work as far as objectives are concerned, advise him regarding methods of attaining these, and contribute materially to the proper utilization of results.

Another objective of organization is the coordination of work. Most projects require for their completion the solution of a number of problems. These may be quite separate scientifically, but they have to be considered in relation to each other from the standpoint of time, cost, and technical results. Therefore, it is essential that the various persons working on the separate problems act as a team under the leadership of someone in charge of the entire project.

The purpose of the organization, then, is to insure these objectives, to define responsibility, and yet to leave to the individual as much scope for his initiative as his ability and experience seem to justify.

Usually the research men will be assigned to work with a group on some problem that has been selected by the management because it is important to the company and because the probability of its solution is sufficiently high to justify the effort. If the worker possesses the necessary qualifications he will have, to a considerable degree, the quality of imagination and the creative urge, and therefore may have ideas of his own, not relating to the problem in hand, on which he would like to do some work. But if he also possesses the qualities of practicality and cooperation, this situation will not cause him concern. In most organizations men are encouraged to have new ideas, and to present them in written form to the management. In some cases the management's policy may be to have some preliminary work done by workers on such ideas. In other cases, definite authorization is required for any such work. The decision will depend not only on the organization but also on the immediate importance of the work in hand, and on the apparent value of the new idea. An objective and practical attitude toward this matter is necessary, with an effort to consider it from the standpoint of the management, without, however, losing interest in the desirability of having the idea evaluated whenever this can be done.

When the worker's idea relates to the problem in hand, he will usually find that it is given early consideration, but here again a somewhat objective attitude is desirable, including a careful consideration of the point of view of others who may have relevant knowledge.

Dilemmas of this sort are brought about by the existence of one of the qualities which underlies the ability to do useful research, namely, the creative urge, and a proper solution of such dilemmas is of the utmost importance to both the worker and the organization.

Aids to the worker.—The scientific research student in a university laboratory in most cases has to do practically all the work relating to his problem. Particularly in the larger industrial research laboratories, he will find a different state of affairs. Library facilities will be available to assist in literature searches and the preparation of bibliographies. Routine tests and analyses will be made by service departments. He will thus be able to work more effectively and to concentrate his efforts on planning and experimentation.

These service facilities are not, however, a substitute for experience. He will as rapidly as possible familiarize himself with the principles underlying them, and with the special techniques of his industry. In some organizations the importance of this is recognized by having all new research workers serve a brief apprenticeship in the service departments.

Another important aid to the research worker is discussion with others in his organization, including particularly those outside the technical unit. Such conferences give him an excellent opportunity to acquire knowledge regarding the practical and commercial phases of the problem. They also help develop the important arts of discussing technical matters in ordinary English, and of presenting ideas and facts clearly.

Progress of the Research Worker

The purpose of this part of the discussion is to outline the possible progress of the research worker, with particular reference to the role played by the various qualities and abilities discussed earlier.

Subordination versus assumption of responsibility.—Here we are stating the subject as a dilemma, and the solution depends on a number of circumstances including the degree to which the worker and his superior possess a number of the qualities discussed under "Qualifications for a Career in Research." A properly qualified superior will encourage those working with him to take responsibility to as great a degree as possible. A properly qualified research worker will accept responsibility to as great a degree as he is permitted. This being the case, the only question then is what is meant by "possible." Someone must be responsible for the success of the entire project and the final decision rests with this individual.

This situation may be clarified by the following method of approach. The worker is spending the employer's money in an endeavor to solve a problem. This expenditure includes, in addition to the worker's salary and materials used, part of the salary of those who supervise him, particularly his immediate superior. He is therefore entitled to a reasonable amount of assistance from his superior, but he will become a more efficient worker to the extent to which this need is reduced.

An equally good approach was suggested by a commentator.

> I have frequently heard reference to the desirability of a man learning to distinguish between the three cases; first, a decision which he is entitled to and should make on his own responsibility; secondly, a decision which he should make but of which he should inform his superior; and third, a decision requiring the authorization of his superior before it is consummated. If a man in research can learn to distinguish as to these three cases, he will increase his own responsibility and function efficiently as a member of the organization.

As the worker progresses he may find that he is faced with two types of responsibility. In the first place it may be his responsibility to carry a project through to successful completion, then later he may be faced with the responsibility for supervisory and executive work. It is here that other qualities such as leadership, common sense, and judgment will become increasingly important.

Acquisition of experience.—In industrial research, experience plays a role of peculiar importance. The scientist who has done research work in connection with his postgraduate course knows the importance of thoroughly studying the literature on a subject before he starts to work on it. When he enters an industrial research organization he will probably find that the same necessity exists, but that the facilities for acquiring this information are quite different and more complicated. Most of the process industries, at least, did not have technical origins, but started as arts or handicrafts. Progress in the early stages was largely empirical and was in many cases the result of inventive ability rather than thorough study. To make his efforts of the greatest usefulness the research worker must familiarize himself with those parts of the industry which are related to his work. He must not assume that because a process cannot be explained or a material described in precise scientific terms it is outside his field of interest. Much of the work of an industrial research laboratory consists in the wise application of technology to just such situations.

It has frequently been found, however, that too much experience in a field may blind a person to the possibility of doing something quite different and better. Information derived through experience should be treated as the best information available at that time, but subject always to further change.

Evaluation and utilization of ideas.—As the worker progresses in his career he will find that his ability to evaluate and to utilize ideas is a matter of considerable importance, whether the ideas are his own or come from another source. This ability depends in part on his training and experience, and in part on temperament. He should cultivate the habit of taking a constructive rather than an instinctively destructive attitude toward new ideas. By "constructive" we do not mean blind optimism but rather an attitude of examining an idea carefully and making a conscientious effort to use whatever is good. If part of the idea is unsatisfactory he may attempt to replace it with something better. He should not make undue use of scientific facts or principles to destroy new ideas. He should particularly remember that the principal use of scientific theories is to suggest action and should not get into the habit of developing theories for the purpose of discouraging action on new ideas. "A destructively critical attitude will discourage others from giving ideas."

Leadership.—As the research worker progresses in the organization other technical people are usually assigned to work with him. The word "with" is used advisedly, because in most research organizations the emphasis is on cooperation rather than subordination. His attitude should be that of giving encouragement and assistance to such men as have been assigned to work with him and of giving them every facility to do their work with as little interruption or digression as possible. To get the best results he must be scrupulously careful to make sure that his men get full credit for what they do. He should study his personnel carefully, because much of the success of a scientific organization, whether large or small, depends upon having men do the work for which they are best suited. His studies should relate not only to the abilities of his men but also their temperaments. He should inspire his men with confidence. They should not only be confident of his ability to direct their work but they should also be confident of their own ability to do it. To secure this result he must know how and when to encourage or criticize, and his manner of doing this should be adapted to the peculiarities of the person with whom he is dealing.

Ability to complete as well as start work.—Young men in business are frequently criticized because they seem to be much better at starting work than at finishing it. Industrial research workers are no exception, and this difficulty is not confined to the young. It appears to arise in part from the incompatability of certain of the qualifications discussed in the first part of this report. Self discipline will help to correct this tendency. Some men, particularly in their earlier years, find it difficult to persevere toward a definite goal because their imagination and creative urge continually present to them new and therefore more attractive ideas that divert their attention. In other cases, the worker will tend to become interested in one particular phase of his work, the subject matter of which may appeal to him for its own sake. In both cases the remedy is for the man to have a clear appreciation of the objective of his work and a realization that the objective is the important thing to attain. In other cases the worker may tend to spend too much time on one particular phase of a subject because he feels that there he is safe, and because he lacks the courage to do something new and unorthodox.

In still other cases, the difficulty may relate more to the problem than to the man. As problems progress, factors are frequently involved which are outside the purely scientific domain in which the research worker is primarily trained. For example, forms of apparatus that have been used in laboratory experimentation may have to be modified or even replaced by something quite different. Economic questions may become important. Here it is that adaptability and versatility enter. The usefulness of the research worker will be greatly enhanced if he has sufficient perspective to recognize the importance of these problems and is sufficiently versatile or resourceful to assist in solving them. This is true, even though he may not be primarily responsible for the larger scale development. If the research man finds that he lacks the proper training to permit him to cope with these factors he should acquire it by outside reading and by conversation with those who have such training.

Planning.—The first step in the successful solution of a research problem is to have an objective that is properly defined, stated, and understood. Much of the work done in universities by graduate research workers consists of finding new facts. While the objective may be apparent in many industrial problems, insofar as approach is concerned, it is not so simply stated. The work frequently arises from some need, and the objective is to meet this need, subject to certain requirements. In other cases, the purpose may be to apply new facts to existing conditions, to effect an improvement, or to find a use for new facts. These are the broad objectives of many industrial problems, and an understanding of them is desirable. It is especially important for the worker to have a thorough understanding of the purpose of the particular part of the work for which he is responsible, including the application of the results to the company's needs. A clear understanding of the immediate objective of his work will assist him in laying his plans and in executing them, and in bringing out details which might otherwise be overlooked. If he constantly keeps the objective in mind he will be less likely to digress into bypaths or waste time on nonessentials; he will realize that every step and every experiment should be so planned that its successful accomplishment will bring him nearer his objective.

On this point a reviewer makes the following pertinent comment.

> It is of interest from time to time to estimate the period that would have been required to complete a problem if no experiment had been wasted. That is, once we have finally completed a research project, how much time would be necessary to conduct the essential work to prove the given point. Frequently, this would be a very small fraction. Hence the incentive to careful planning.

Another pertinent comment on this section was made by a research director.

> The important side is entirely mental and experimentation is for the purpose of confirming the ideas. Successful research does not depend upon the volume of experiments but upon clear

thinking, planning and observation so that maximum information is obtained from each experiment.

Essentials and nonessentials.—In doing scientific work in industry there is frequently a temptation to spend more time than is necessary on certain features of the work. This may be because the subject matter of this portion of the work appeals to the worker or because facilities or previous experience are available. Here again a proper appreciation of the objective will serve as a guard against this type of inefficient planning.

Experiments should be so planned that the results will be, as far as possible, unequivocal.

In planning research work there should be due appreciation of the relationship of the cost of the work to its ultimate value. The cost of planning work is generally small compared with the cost of doing it, and it may pay to spend considerable time in careful planning. In most cases progress is made by consecutive steps, that is to say, one set of experiments will lead to one conclusion and further work will be based on this conclusion. Expense will be reduced if work is laid out so the experiments will be carried out in logical order.

Execution.—While it is not possible, of course, in a report of this sort to make any detailed suggestions regarding the execution of research work, a few points warrant mention.

One of the problems that frequently faces the industrial research worker is that of suitable apparatus. In many cases the standard forms of apparatus are not suited to the work, and special apparatus has to be provided. Means of securing this differ with the organization, but it is true that in many cases considerable time may be required. The extent of refinement demanded should be in proportion to the needs of the case. If the first experiments are of a preliminary nature the research worker may find that by canvassing the available facilities of the establishment, discussing the matter with his fellow workers, and using his own ingenuity he can secure equipment adequate for the immediate purpose with comparatively little effort. Important developments have often been started with makeshift apparatus. Another suggestion is that fullest use should be made of related information. This has been emphasized previously in connection with the acquisition of experience.

Future of the Research Worker

In most research organizations it is felt that a career is offered in the organization itself for the right kind of man. Experience in a research organization may also give a man a training that will qualify him for positions involving great responsibility in other parts of the company. Frequently men are transferred from the central research organization to positions in the operating and sales departments. Whether or not this occurs depends on the qualifications and preferences of the individual.

There is a growing tendency in some industries to fill positions in other departments with men of research training. This is particularly true of industries built on research, and whose products are used by other industries.

Compensations of the Research Worker

Industrial research offers to the properly qualified man an opportunity to make a good living. Although accurate and complete data on financial compensation are not available, it is believed that, on the average, scientific men in industry fare as well in this respect as men of comparable age, experience, and ability in other industrial activities. This statement is made with some reservation owing to the great differences which exist, especially between industries. On this point one laboratory reports: "Our salaries in this laboratory run 5 to 10 percent above those in our engineering department for men with corresponding training and experience."

A chemist or engineer is rarely required to serve a low-paid apprenticeship comparable with that required of a doctor or lawyer.

It would be difficult to make any definite quantitative comparison, as to financial compensation, between industrial research and other activities. After the initial start, compensation is a highly individualistic affair.[1] One survey of a number of laboratories led to the conclusion that—

> so far as this particular group of laboratories is concerned, anything even approaching a common ground of agreement as to the market value of any particular type of research work, any particular educational background or any particular amount of experience, skill or qualities of character, simply does not seem to exist.

This is probably because research itself is an individualistic affair, and the usefulness of an individual to an organization cannot be expressed in terms of any simple standards, such as age or experience, applicable to a large group of individuals.

One research director points out that there is a lower turn-over of research workers than of men in other business activities. Although quantitative data are not available, it is certainly to the interest of all that this should be procured.

In addition to financial compensation, there are a number of other compensations derived from a career in industrial research which are frequently overlooked. One of these is the satisfaction a man derives from his vocation. A man who possesses the creative urge and scientific curiosity to a high degree, and this has been characteristic of the great men of science, will probably be happier in scientific work than in any other activity.

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[1] From a report of the Industrial Research Institute.

This is true whether the man is interested in finding new facts to extend our boundaries of knowledge or in the development and application of new techniques, or has an urge to discover.

Another compensation is the satisfaction derived from doing work that may be of lasting benefit. If his work results in a new product, the research man will derive ultimate satisfaction from the fact that this product has not only been of benefit to his own organization but has supplied some public need. If his work has led to the establishment of some new scientific truth, the use of this by his fellow scientists will be an inspiration to him. It is important that men who have made valuable contributions receive from their employers proper and timely recognition for their work.

Compensation also results from the feeling that one's work, although on a small scale, may have results of enormous economic importance. The young research worker will frequently play an important role in work of more lasting and objective importance than the young man with a similar period of experience in another occupation.

The desire to receive public recognition of one's work is very natural. Formerly one of the principal distinctions between scientific workers in universities and those in industry was that the former were permitted to publish their work, whereas it was generally believed that the latter were not. At the present time most industrial research laboratories not only permit, but encourage, workers to publish the results of their work when such publication will not be prejudicial to the interests of the company.

Probable Future of Industrial Research as a Career

Any discussion of industrial research as a career should properly include a consideration of the future. Research has been a part of our industrial structure for about 40 years, but during the first two decades of that period it was barely getting under way. Most of the expansion has occurred during the past 20 years. Although the results have been most impressive, it is not yet a large factor in our industrial life from the standpoint of the number of persons employed or of the expenditures relative to the value of products manufactured. There is ample margin for growth. Some of the reasons for further growth are: (1) The growing realization by industrialists and investors that research pays; (2) the pressure of competition both from within and from without an industry, which supplies an incentive to develop new and improved methods, and improved products; (3) the desire for expansion and diversification of products, which leads to work on new products; (4) new discoveries and inventions, including particularly new raw materials.

All indications point to the permanence of industrial research and to its future growth. Based on the experience of the past few years, it appears likely that the rate of growth will increase. One commentator makes the prediction that—

> the saturation point is not likely to be reached until all industry, on the average, spends about three percent of its effort on research and development. This would allow for a manifold increase within the period of time we can roughly foresee now. Instead of fifty thousand employees in research, ***one million*** is not too many to look forward to over the period of the next forty years.

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SECTION II

7. RESEARCH AS A GROWTH FACTOR IN INDUSTRY

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ABSTRACT

Research is receiving increasing recognition from industrial management as a means of expanding earning power through the development of new products and processes. That it has played an important part in the growth of many companies and industries can readily be demonstrated. To the investment analyst, the research expenditures of various companies therefore constitute an important factor in determining their long-term outlook. Because of inadequate data, it was necessary to estimate such expenditures based upon the number of workers engaged. A survey was made of a cross section of American industry to determine the average expenditure per worker and this was applied to the number of workers reported to the National Research Council. The estimated aggregates by industry were related to the value added by manufacture in 1937. The results showed wide variation among industries in research expenditures per $100 value added by manufacture, indicating vast opportunities for profitable research in many industries in which it is at present relatively neglected.

Scientific research is one of America's fastest growing industries. That it plays a vital role in the development of new products and processes has in recent years received increasing recognition from those who occupy positions of responsibility in practically all lines of production. The rapid growth of industrial research laboratories and personnel in the United States over a period of years has been clearly demonstrated; it remains only to translate these findings into dollars and cents.

Those who direct the flow of capital have been a little more remote from industrial operations, where science's discoveries and inventions bear fruit, than those who actually supervise production, and it is not surprising that they have been a little slower to grasp the importance of research. But what they have lacked in promptness they have made up in enthusiasm and today we find the case for research being presented by many companies in their annual reports to stockholders.

The widening acceptance of the thesis that research promotes the growth and increases the earning power of companies is based upon records of a great number of cases where this has occurred rather than on any comprehensive analysis of data for industry as a whole. It has been noted that those industries which have been most active in research have shown the best growth trends.

What has been true of industries has also been true of individual companies. Generally speaking, those companies which are outstanding in their research activities are those which shape up as the best managed and successful enterprises. The ability to take advantage of the possibilities of research in expanding sales and otherwise increasing earning power is a very good indicator of the alertness of management.

The vital role of research in the chemical and other rapidly expanding lines, where the emphasis is on the continuous development of new products, has been pointed out frequently. That research deserves a large part of the credit for the steady growth of the leading chemical and electrical equipment companies is widely recognized.

It is also well known that the rapid growth in consumption of aluminum, nickel, vanadium, tungsten, chromium and molybdenum, and other light or alloy metals is due largely to research in developing new uses for these metals. Research holds forth similar possibilities for magnesium, beryllium, and many of the lesser-known metals.

The possibilities of research in the more seasoned industries, however, are not so obvious. Yet there are numerous cases of companies which have been enabled to make a better than average showing or even counteract an unfavorable trend in their established lines through the development of new products.

This was strikingly illustrated in the agricultural equipment field during the past decade. For some time it looked as though the mechanization of the farm had gone about as far as it would. Then one company surveyed the agricultural scene and found that mechanization had not been extended to the small farm of less than 100 acres. It brought out a 1-plow tractor and a 5-foot combine, which the trade predicted would not sell. They not only sold but substantially increased this company's share of the market and competitors were soon in the field with new models of their own design.

The influence of research on the growth of industries has been clearly shown in the development of the Diesel engine. For years the applications of the Diesel engine had been limited to stationary power and marine uses. Gradually the light-weight, high-speed engine was developed. In recent years, the Diesel was applied in trucks, tractors, and locomotive-units and the companies which developed these new uses have notably bettered their competitive positions in their various fields.

The accumulation of many such cases almost forces the conclusion that there is a positive correlation between research expenditures and growth in earning power. This, however, is rather difficult to measure because of the lack of a generally accepted definition of research, the secrecy on the part of many companies regarding expenditures and the time lag between such expenditures and an earnings return. Research expenditures represent a sacrifice of immediate earnings in anticipation of a greater return later on, the time lag being greater in the case of pure research than in the case of product development.

In view of the importance of research as a factor in the growth of companies and industries, it was decided to tabulate the size of research personnel and expenditures for a number of leading companies representing a broad cross section of American industry. Accordingly the following letter was directed to a selected list of companies:

> As an investment counsel organization, we are making a study of research expenditures in various industries. Will you be good enough to give us the following information with reference to your company:
>
> "The approximate amount spent for scientific research and development of products in each of the past few years and the number of men engaged in such work."
>
> While it is our intention to make the conclusions drawn from our study available to industry generally, we shall treat any information pertaining to your particular company confidential, if so requested.

Since the primary purpose of the inquiry was to obtain whatever data on research might be available, the request was worded in very general terms, leaving it to the individual companies to determine such expenditures in accordance with their accounting policies. It soon became obvious that there was wide variation in the definition of research and that such data had little value for comparing the activities of individual companies. Furthermore, many companies which had reported their research personnel to the National Research Council, refused to give out any information on expenditures. Obivously, a statistical tool was needed for estimating expenditures on a comparable basis.

The first figure sought was the average research and development expenditure per worker, including both salaries and the pro rata cost of supplies, equipment, and overhead. Once this was obtained, it would be possible to estimate the expenditures for each company and also for industry as a whole, based on the number of workers reported to the National Research Council, which data are probably more nearly comparable than any other.

From all the replies received, those were selected which stated both the number of personnel and expenditures for research and development. While there is undoubtedly considerable difference of computation among companies, the ratio between the number of workers and expenditures for any one company is highly significant, since they both come under that particular company's definition of research, whatever it may be.

Although replies were received from a great many additional companies, which gave incomplete data, 31 companies reported both the personnel and expenditures for research and development in 1937. This is summarized in the following tabulation, without revealing the names of the individual companies, which furnished this information in confidence.

Reported research expenditures and personnel for representative companies—1937

Company No.	Reported research expenditure	Reported number of research workers	Research expenditure per worker
1	$9,363,000	2,000	$4,682
2	5,000,000	1,500	3,333
3	3,821,956	1,504	2,541
4	2,525,613	686	3,682
5	2,500,000	600	4,167
6	1,800,000	400	4,500
7	1,600,000	550	2,909
8	1,500,000	225	6,667
9	1,250,000	303	4,125
10	1,000,000	195	5,128
11	1,000,000	165	6,061
12	750,000	285	2,632
13	740,000	177	4,181
14	600,000	200	3,000
15	600,000	80	7,500
16	557,000	189	2,947
17	500,000	200	2,500
18	442,000	145	3,048
19	434,000	166	2,619
20	400,000	75	5,333
21	375,000	40	9,375
22	300,000	150	2,000
23	300,000	60	5,000
24	248,400	36	6,900
25	200,000	60	3,333
26	200,000	50	4,000
27	159,000	20	7,950
28	78,000	17	4,588
29	77,000	22	3,500
30	60,000	10	6,000
31	20,000	3	6,666
Total	38,400,969	10,113	3,797

These 31 companies in the aggregate reported for 1937, research and development expenditures of $38,400,969 and personnel of 10,113. The indicated average expenditure per worker was $3,797. There was considerable variation among companies in the average expenditure per worker, which ranged all the way from $2,000 to over $9,000. Although there was no definite relation between size of company and average expenditure, there was a tendency toward larger average expenditures in the cases of the smaller companies.

The sampling represents approximately one-fifth of the total 49,564 research workers in the United States in 1938, reported to the National Research Council. Inasmuch as there is a preponderance of large companies in the sampling, the average expenditure per worker is probably a little low. For all industry, it is probably close to $4,000. The sampling by various industries was not sufficient to warrant any conclusions as to variations by industry, although such variations may be considerable.

Some corroboration of this figure is obtained in the case of the steel industry for which data on both research personnel and expenditures are available. The American Iron and Steel Institute reported that the industry spent in 1939 a total of $10 million for research and employed nearly 2,550 chemists, metallurgists, physicists, and other trained scientists full time and 1,300 others on a part-time basis.[1] This would be equivalent to $3,922 per full-time worker. If half of the part-time workers are added, however, the average expenditure would be reduced to $3,125, which seems too low. The higher figure is quite close to the average obtained for the 31 companies representative of all industries.

On the basis of $4,000 per worker for 49,564 reported as engaged in research in 1937, the total expenditure in all industrial research laboratories would have been approximately $200 million. This represented 0.29 percent of national income produced of $70 billion.

On the same basis, research expenditures were estimated for each of the major industrial groups and shown as a percentage of the "Value added by manufacture" in 1937 (U. S. Census of Manufactures).[2] This was facilitated by the fact that the Work Projects Administration National Research Project[3] generally followed the Census classification of industries.

Estimated research expenditures by industrial groups

	Number of research workers, as classified	Number of research workers, as adjusted [1]	Estimated research expenditures (in thousands of dollars)	Value added by manufacture (in thousands of dollars)	Estimated research expenditures percent value added by manufacture
MANUFACTURING INDUSTRIES					
Food and kindred products	1,424	1,593	6,372	$3,354,242	0.19
Textiles and their products	367	411	1,644	2,972,485	.06
Forest products	192	215	860	1,265,600	.07
Paper and allied products	752	842	3,368	852,695	.39
Chemicals and allied products	9,542	10,678	42,712	1,793,583	2.38
Petroleum and its products	5,033	5,632	22,528	[2] 2,001,002	1.13
Rubber products	2,250	2,518	10,072	368,772	2.73
Leather and its manufactures	78	87	348	592,043	.06
Stone, clay, and glass products	1,404	1,571	6,284	872,746	.72
Iron and steel and their products not including machinery	1,531	1,713	6,852	3,432,674	.20
Nonferrous metals and their products	1,197	1,339	5,356	856,759	.62
Agricultural implements (including tractors)	1,805	2,020	8,080	278,265	2.90
Electrical machinery, apparatus and supplies	4,114	4,604	18,416	1,102,134	1.67
All other machinery	2,320	2,596	10,384	2,086,705	.50
Motor vehicles, bodies and parts	1,953	2,185	8,740	804,945	1.08
All other transportation equipment	131	147	588	1,081,189	.05
Miscellaneous manufacturing	1,763	[3] 1,973	[3] 7,892	1,078,432	([3])
Total above industries		40,124	160,496	24,894,272	.64
NONMANUFACTURING INDUSTRIES					
Electrical communication	4,202	4,702	18,808	....	....
Utilities (gas, light, and power)	1,000	1,119	4,476	....	....
Consulting and testing laboratories	2,663	2,980	11,920	....	....
Trade associations	571	639	2,556	....	....
Total nonmanufacturing industries	8,436	9,440	37,760	....	....
Grand total	44,292	49,564	198,256	....	....

[1] Classification reported by W. P. A. National Research Project, based on data compiled by National Research Council has been adjusted for various groups to bring total workers to 49,564, which had been reported for all industry but not classified.

[2] Sum of $1,513,340,000 value of crude petroleum at wells in the United States (U. S. Bureau of Mines), plus $587,662,409 value added by manufacture. This adjustment has been necessary to make figures comparable with number of research workers which included those engaged in oil producing as well as refining operations.

[3] In addition to Census of Manufactures' "Miscellaneous industries," includes railroads, steamship companies, retail and wholesale firms, and other service industries which reported comparatively small research employment and which are not classified separately.

Estimated research expenditures per $100 value added by manufacture in 1937 were as follows for the principal industrial groups:

Agricultural implements (including tractors)	$2.90
Rubber products	2.73
Chemicals and allied products	2.38
Electrical machinery, apparatus and supplies	1.67
Petroleum and its products	1.13
Motor vehicles, bodies, and parts	1.08
Stone, clay and glass products	.72
Nonferrous metals and their products	.62
All other machinery	.50

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[1] Steel industry's 1939 research expenditures total $10,000,000. *Steel Facts*, No. 35, 4 (August 1939).

[2] U. S. Department of Commerce, Bureau of the Census. Biennial census of manufacturers—1937. Washington, U. S. Government Printing Office, 1939.

[3] Perazich, G., and Field, P. M. Industrial research and changing technology. Philadelphia, Pa., Work Projects Administration, National Research Project, *Report No. M-4*, 1940.

Paper and allied products	$0.39
Iron and steel and their products not including machinery	.20
Food and kindred products	.19
Forest products	.07
Textiles and their products	.06
Leather and its manufactures	.06
Transportation equipment other than motor vehicles	.05
All manufacturing industries	.64

The manufacturing industries in the United States in the aggregate spend for scientific research only $0.64 out of every $100 value added to goods, two-thirds of 1 percent of the total value added by manufacture. That this could profitably be increased is indicated by the fact that certain industries find it pays to spend more than 2 percent. The majority of industries, if not all of them, are far from the point where the law of diminishing returns will make further expenditures less profitable. Probably the greatest opportunities from the standpoint of capital lie in those industries which have not yet fully awakened to the possibilities of research in expanding markets and increasing earning power. It is likely that the most rapid increases in research efforts will occur in some of those lines where it is now neglected. Competition will help to bring this about, for no industry or company can long maintain its trade position, if it fails to keep up with the procession. Research will no doubt continue to be one of America's fastest growing industries—a fountain of perpetual youth for the old and new alike.

Summary and Conclusions

1. The importance of scientific research as a growth factor in industry is receiving increasing attention from a financial and investment standpoint. Although difficult to measure, there is undoubtedly a correlation between research expenditures and the growth of companies and industries. This view is supported by numerous case histories.

2. Based on a survey of 31 companies representing a broad cross section of American industry and accounting for one-fifth of total research workers in the United States in 1937, the average expenditure was found to be close to $4,000.

3. Total research expenditures in industrial laboratories in the United States in 1937 have been estimated at approximately $200 million, equivalent to 0.29 percent of national income produced. The average research expenditure per $100 value added by manufacture was $0.64.

4. Research expenditures by industries showed wide variation. There are vast opportunities for increasing earning power through expanding research activities, particularly in those industries in which it is now relatively neglected.

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SECTION II

8. INDUSTRIAL RESEARCH EXPENDITURES

By Karl T. Compton

President, Massachusetts Institute of Technology, Cambridge, Mass.; Chairman, Advisory Committee to the National Association of Manufacturers, Committee on Patents and Research

ABSTRACT

A summary of findings on the relation of research expenditures to annual gross sales income in 181 companies.

Member companies of the National Association of Manufacturers, in a letter dated April 2, 1940, were asked:

> What percentage of your normal annual gross sales income do you spend for research?

The letter accompanied a questionnaire prepared by the National Research Council for its Survey of Research in Industry with which the National Association of Manufacturers cooperated.

Responses received numbered 892, of which 203 included reports of research expenditures. The sample reporting expenditures represents about 8 percent of the known industrial research laboratories.

The median expenditure of the companies for industrial research was found to be 2 percent of gross sales income. The percentage was highest in small companies. The chemical and allied products industries, on the other hand, ranked the highest in percentage of gross income for research.

Following is a summary of the replies:

Companies reporting research expenditures (number)	203
Usable returns on relation of research expenditures to sales (number)	181
Median expenditure (percent)	2

Distribution:	*Number of companies*
Less than 1 percent	43
1 to 2 percent	49
2 to 3 percent	36
3 to 4 percent	22
4 to 5 percent	3
5 to 6 percent	13
6 to 7 percent	4
7 to 8 percent	0
8 to 9 percent	1
9 to 10 percent	1
10 to 11 percent	7
11 to 12 percent	1
12 to 13 percent	1

Break-down by sizes of companies

Companies reporting research expenditures (number)	181
Usable returns as related to capitalization (number)	151

Capitalization	Number of companies	Median expenditure for research
		Percent
$20,000 to $75,000:		
1 to 2 percent	1	
5 to 6 percent	2	
8 percent	1	
Total	4	5
$100,000 to $500,000:		
Less than 1 percent	5	
1 to 2 percent	6	
2 to 3 percent	6	
3 to 4 percent	2	
4 to 5 percent	1	
5 to 6 percent	4	
6 to 7 percent	1	
10 to 11 percent	1	
12 to 13 percent	1	
Total	27	2½
$500,000 to $1,000,000:		
Less than 1 percent	3	
1 to 2 percent	4	
2 to 3 percent	3	
3 to 4 percent	4	
5 to 6 percent	2	
6 to 7 percent	1	
Total	17	2½
$1,000,000 to $2,000,000: [1]		
Less than 1 percent	7	
1 to 2 percent	10	
2 to 3 percent	12	
3 to 4 percent	8	
5 to 6 percent	1	
6 to 7 percent	2	
10 to 11 percent	1	
Total	41	2
$2,000,000 to $5,000,000:		
Less than 1 percent	3	
1 to 2 percent	6	
2 to 3 percent	3	
3 to 4 percent	2	
11 to 12 percent	1	
Total	15	1½
$5,000,000 to $10,000,000:		
Less than 1 percent	5	
1 to 2 percent	3	
2 to 3 percent	1	
3 to 4 percent	1	
Total	10	1
$10,000,000 to $50,000,000:		
Less than 1 percent	10	
1 to 2 percent	8	
2 to 3 percent	3	
5 percent	1	
Total	22	1
$50,000,000 to $100,000,000:		
Less than 1 percent	4	
1 to 2 percent	2	
2 to 3 percent	1	
9 percent	1	
Total	8	Less than 1
Over $100,000,000:		
Less than 1 percent	4	
2 to 3 percent	1	
3 to 4 percent	1	
5 to 6 percent	1	
Total	7	Less than 1

---

[1] In this category were included all companies reported by Dun & Bradstreet as having capitalization "over 1 million dollars" but for whom specific [illegible] available.

Break-down by types of industries

Industry		Number of companies	Median expenditure
			Percent
Chemicals and allied products:			
Less than 1 percent	2		
1 to 2 percent	4		
2 to 3 percent	7		
3 to 4 percent	7		
5 to 10 percent	4		
10 to 13 percent	4		
Total		28	3 to 4
Miscellaneous industries:			
1 to 2 percent	1		
2 to 3 percent	4		
3 to 4 percent	3		
5 to 6 percent	2		
Total		10	3
Machinery, not including transportation equipment:			
Less than 1 percent	6		
1 to 2 percent	13		
2 to 3 percent	10		
3 to 4 percent	8		
4 to 5 percent	1		
5 to 6 percent	4		
6 to 7 percent	2		
10 to 11 percent	2		
11 to 12 percent	1		
Total		47	2
Transportation equipment, air, land and water:			
1 to 2 percent	6		
2 to 3 percent	2		
5 to 6 percent	2		
6 to 7 percent	1		
9 to 10 percent	1		
10 to 11 percent	2		
Total		14	2
Forest products: Total		1	2
Paper and allied products:			
Less than 1 percent	3		
1 to 2 percent	4		
5 to 6 percent	1		
Total		8	1
Printing, publishing, and allied products, 1 to 2 percent: Total		3	1.3
Stone, clay, and glass products:			
Less than 1 percent	5		
1 to 2 percent	7		
2 to 3 percent	4		
3 to 4 percent	3		
4 to 5 percent	1		
Total		20	1½
Iron and steel and their products, not including machinery:			
Less than 1 percent	12		
1 to 2 percent	7		
2 to 3 percent	5		
3 to 4 percent	1		
4 to 5 percent	1		
Total		26	1
Nonferrous metals and their products:			
Less than 1 percent	1		
1 to 2 percent	3		
5 to 6 percent	1		
Total		5	1
Food and kindred products:			
Less than 1 percent	4		
1 to 2 percent	1		
2 to 3 percent	1		
Total		6	½ of 1
Textiles and their products:			
Less than 1 percent	4		
1 to 2 percent	2		
4 to 5 percent	1		
Total		7	½ of 1
Products of petroleum and coal:			
Less than 1 percent	2		
1 to 2 percent	1		
Total		3	½ of 1
Rubber products:			
Less than 1 percent	1		
1 to 2 percent	1		
Total		2	⅞ of 1
Leather and its manufactures: Total		1	3/10 of 1

Summary of break-down by types of industries

Median expenditure:	*Industries*
3 to 4 percent	Chemicals and allied products. Miscellaneous industries.
2 percent	Machinery, not including transportation equipment. Transportation equipment, air, land, and water. Forest products.
1 percent	Paper and allied products. Printing, publishing, and allied products. Stone, clay, and glass products. Iron and steel and their products not including machinery. Nonferrous metals and their products.
Less than 1 percent	Food and kindred products. Textiles and their products. Products of petroleum and coal. Rubber products. Leather and its manufactures.

While broad generalizations cannot be made from this small sample, it is particularly significant to note the relation of expenditures to sizes of companies and to types of industries in the cases reported.

SECTION III

EXAMPLES OF RESEARCH IN INDUSTRY

Contents

SECTION III

1. RESEARCH IN AERONAUTICS

By J. C. Hunsaker

Professor in Charge, Department of Aeronautical Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

ABSTRACT

The rapid development of an important industry from the Wright Brothers' original invention is attributed to the increasing usefulness of the airplane as successive improvements took place. These improvements resulted from research largely controlled by the Government. Research, conducted at Government expense, has supplied the industry with general information from which industry's own applied research has developed improved aircraft. The airworthiness and safety requirements of the Civil Aeronautics Authority and the competition fostered by the Army and Navy procurement policies have the effect of directing applied research along lines desired by the Government. Competition for superior performance has tended to concentrate the manufacture of airplanes and engines in the hands of a few large concerns that maintain outstandingly able engineering and research organizations. There is nothing in the patent situation to restrict the number of concerns in the industry.

General Discussion

Historical

The aeronautical industry which has grown to adult stature in one generation is a romantic example of technological change profoundly affecting communications, transportation, and national defence. By the beginning of the century, applied science had prepared the ground for the airplane and all of its elements had been experimented with by the pioneers. They knew about the monoplane glider, the trussed biplane glider, the internal combustion engine, the screw propeller, and the launching catapult. While the pioneers had experimented with various means to control flight in a heavier-than-air vehicle, it remained for the Wright Brothers to apply the final and necessary control about the three axes of space required to perfect a practical flying machine.

The Wright airplane, demonstrated for the first time in public in 1908, was a 40-mile-per-hour biplane able to fly with two men for barely an hour. Its safety was precarious and its utility of an extremely low order. No one then inquired about safety. Today transport planes cruise at 200 miles per hour with large loads of passengers and mails, and air-transport lines span oceans and continents with a high degree of safety, comfort, and reliability. Air transportation has become an important business, employing thousands of men directly, and many more in the manufacturing industry that supplies its equipment. The parallel development of the airplane in the national defense, has produced pursuit airplanes that exceed 400 miles per hour in speed, and military bombers that can carry a ton or more of bombs at 300 miles per hour. Naval aircraft include high-performance fighting and observation airplanes carried on vessels of the fleet and large flying boats operating independently as a striking force.

The least thoughtful must observe that air transportation is profoundly changing the geographical factor in our social and political isolation, while the military use of the airplane has created the new concept of air power.

The first chart shows the chronological increase of speed of specially built racing planes since 1910, with a forecast of what may be possible in the next 5 years. These world's records seemed fantastic when first set up, but today's transport planes fly faster than the world's record in 1921, and pursuit planes now exceed in speed the world's record of 1932.

The improvement of the airplane has gone on constantly since the first Wright biplane. No other technological innovation ever had such public support. While the airplane became the object of intensive study and experimentation by governments, young men with the vision of things to come learned to fly and to build improved airplanes. Teachers of science encouraged their students to investigate the new art. Societies were formed to encourage the exchange of information and to promote research and experiment.

The growth of the aeronautical industry in its manufacturing aspect is shown in table 1 in which war fears after Munich are clearly reflected. The charts following table 1 reflect increasing public acceptance of improved service of our airlines.

International Competition in Research

The beginning of organized research was the formation in England of the Advisory Committee for Aeronautics in 1909 under the leadership of the great physicist, Lord Rayleigh. Government research laboratories were later established in France, Germany, Italy, and in the United States. From the first, the best scientific brains throughout the world have helped perfect the airplane.

During the First World War the airplane grew in importance and, by the time of the armistice, multi-engined bombers were making night raids, pursuit airplanes carried cannon and machine guns, and flying boats were making all-day patrols at sea. Command of the air became an objective of national effort.

The modern airplane is the result of increasing knowledge of the aeronautical sciences, applied to the Wright's original airplane. Advances in airplane performance and utility have followed, somewhat discontinuously, new knowledge in aerodynamics, metallurgy, structural design, fuel technology, and engine and propeller design. The steps are sometimes abrupt as inventions or applications occur, such as the National Advisory Committee for Aeronautics cowl and wing engine location, as well as the variable-pitch propeller, and high-octane gasoline. With every such step in advance, the industry has expanded and employment increased. The growth of the industry under competitive conditions has accelerated the improvement of the airplane. Manufacture in this country has now become concentrated in strong concerns that maintain outstandingly able engineering staffs, with ample experimental budgets and superlative test equipment. For example, high-power aviation engines are currently made by three concerns only and propellers by two. In 1939 large air transports were sold by but three firms. This concentration of skill and facilities has come about because of free competition in an art that is rapidly advanced by research.

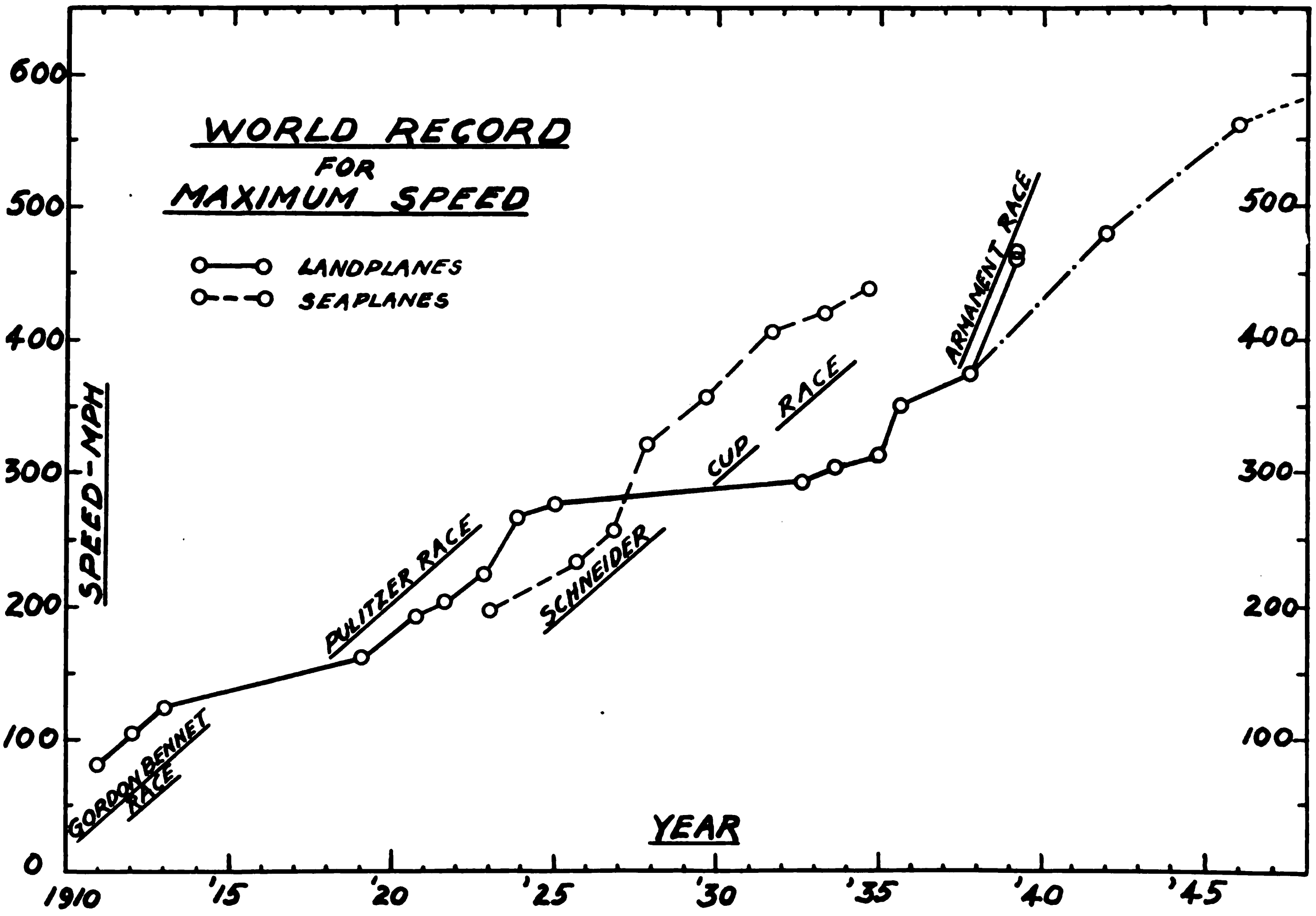


FIGURE 22.—World Record for Maximum Speed

Government policy has also intensified the trend toward concentration because the safety of human life is so decidedly involved that only the very best design and workmanship can be certified as "airworthy" by the licensing authority, and because the procurement policy of the Army and Navy awards contracts for the best performance rather than for the lowest price. When the volume of orders is based on performance resulting from engineering development, a great premium is placed on intensive research. Only the successful bidder recoups his engineering expenses and is in a position to extend his facilities. The result is naturally to concentrate manufacturing of a particular type of airplane in the hands of the most competent firms.

TABLE 1.—*United States aircraft production, 1926–40* [1]

Year	Product	Units	Dollar value (including parts)
		Number	*Dollars*
1926	Planes	1,186	13,000,000
	Engines	842	4,000,000
1927	Planes	1,995	20,000,000
	Engines	1,410	10,000,000
1928	Planes	4,346	43,000,000
	Engines	3,496	20,000,000
1929	Planes	6,193	62,000,000
	Engines	6,504	25,000,000
1930	Planes	3,437	35,000,000
	Engines	4,356	22,000,000
1931	Planes	2,800	33,000,000
	Engines	3,864	14,000,000
1932	Planes	1,396	20,000,000
	Engines	1,959	14,000,000
1933	Planes	1,324	23,000,000
	Engines	1,830	9,000,000
1934	Planes	1,615	25,000,000
	Engines	2,545	16,000,000
1935	Planes	1,568	22,000,000
	Engines	2,965	13,000,000
1936	Planes	2,700	40,000,000
	Engines	4,237	22,000,000
1937	Planes	3,230	56,000,000
	Engines	6,084	30,000,000
1938	Planes	--------	[2] 115,000,000
	Engines		
1939	Planes	--------	[2] 225,000,000
	Engines		
1940	Planes	--------	[3] 500,000,000
	Engines		

[1] War Department restrictions prevent issuing details of production for last 3 years.
[2] Planes and engines.
[3] Estimated planes and engines.

There is nothing to prevent a new concern going into the business, but the new concern must have ample capital and very competent engineers, and be prepared to spend both time and money on applied research in order to offer a product to compete in performance with the leaders. A new concern may begin as a design and research group and continue as such until it can offer an important improvement.

There is nothing in the basic patent situation to prevent more airplane firms being started. The airplane of today is fundamentally the concept of the Wrights, and their patents have expired. While a large number of patents cover modern methods of airplane construction, these are pooled with the Manufacturers' Aircraft Association in a cross-licensing agreement open to all manufacturers who wish to join.

Government Influence on Research

The dominant position of research in aeronautics is essentially no different from its position in other fields

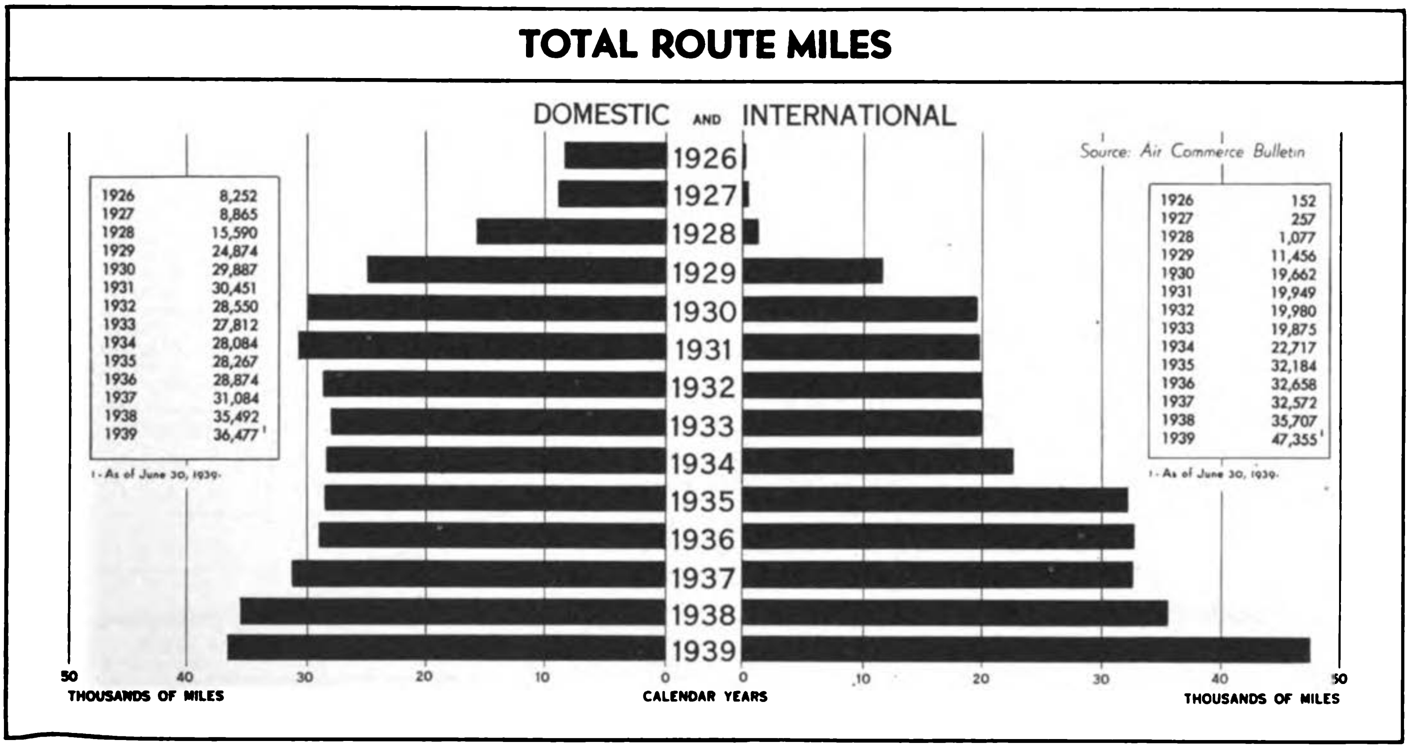


FIGURE 23—Total Route Miles

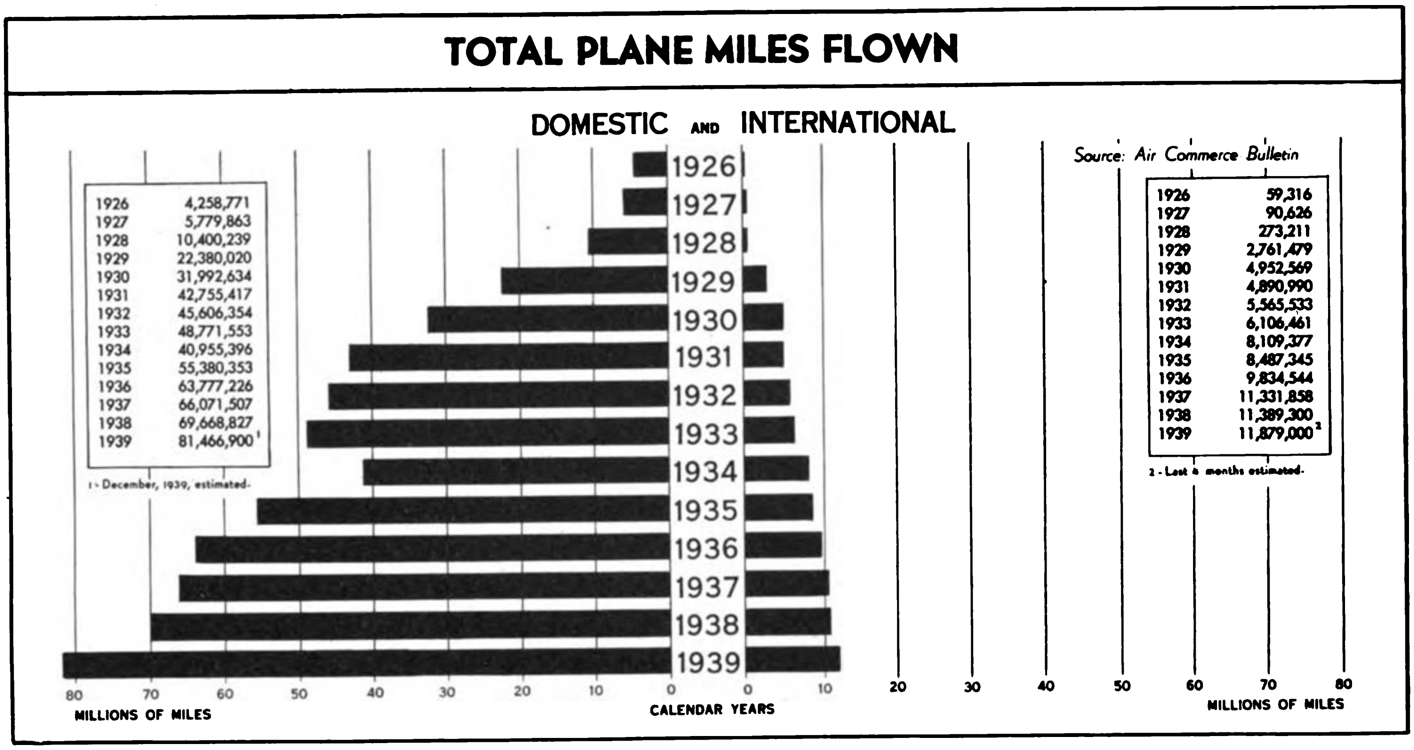


FIGURE 24.—Total Plane Miles Flown

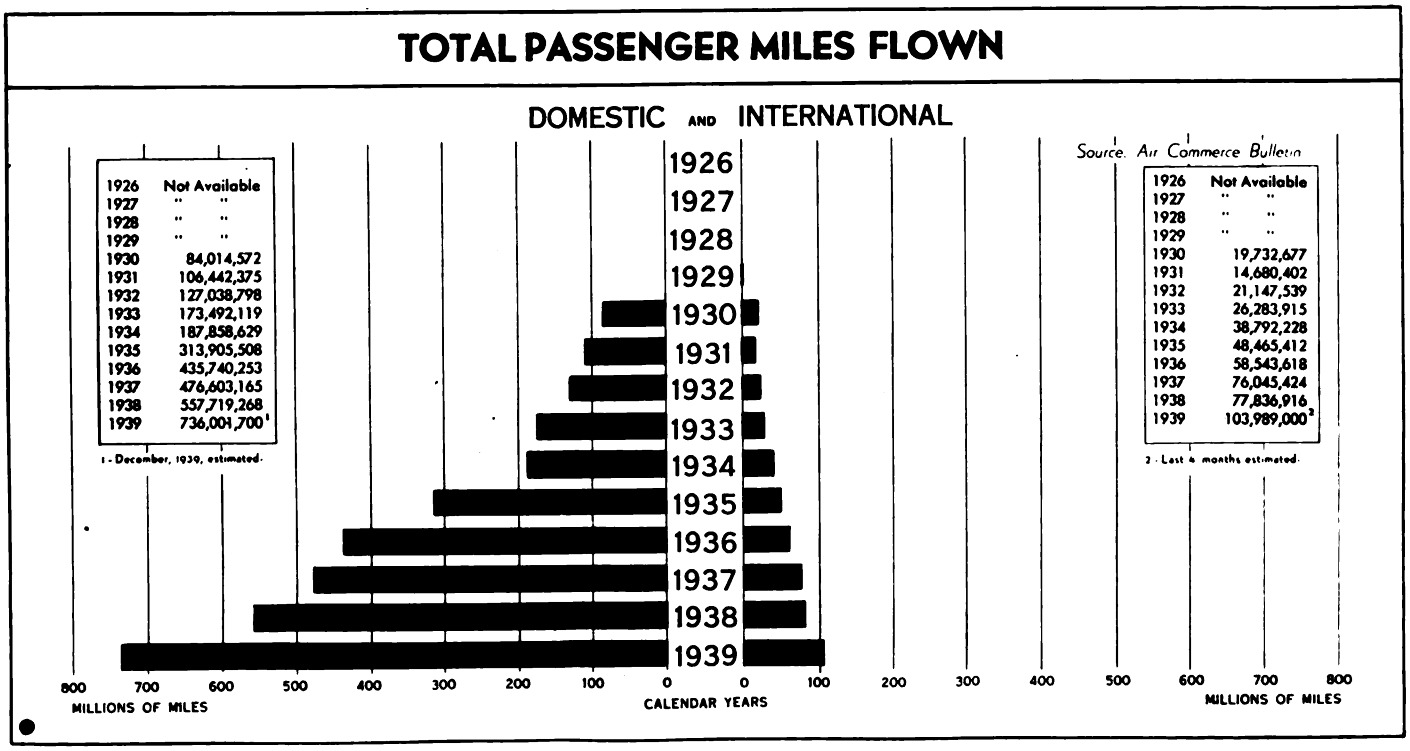
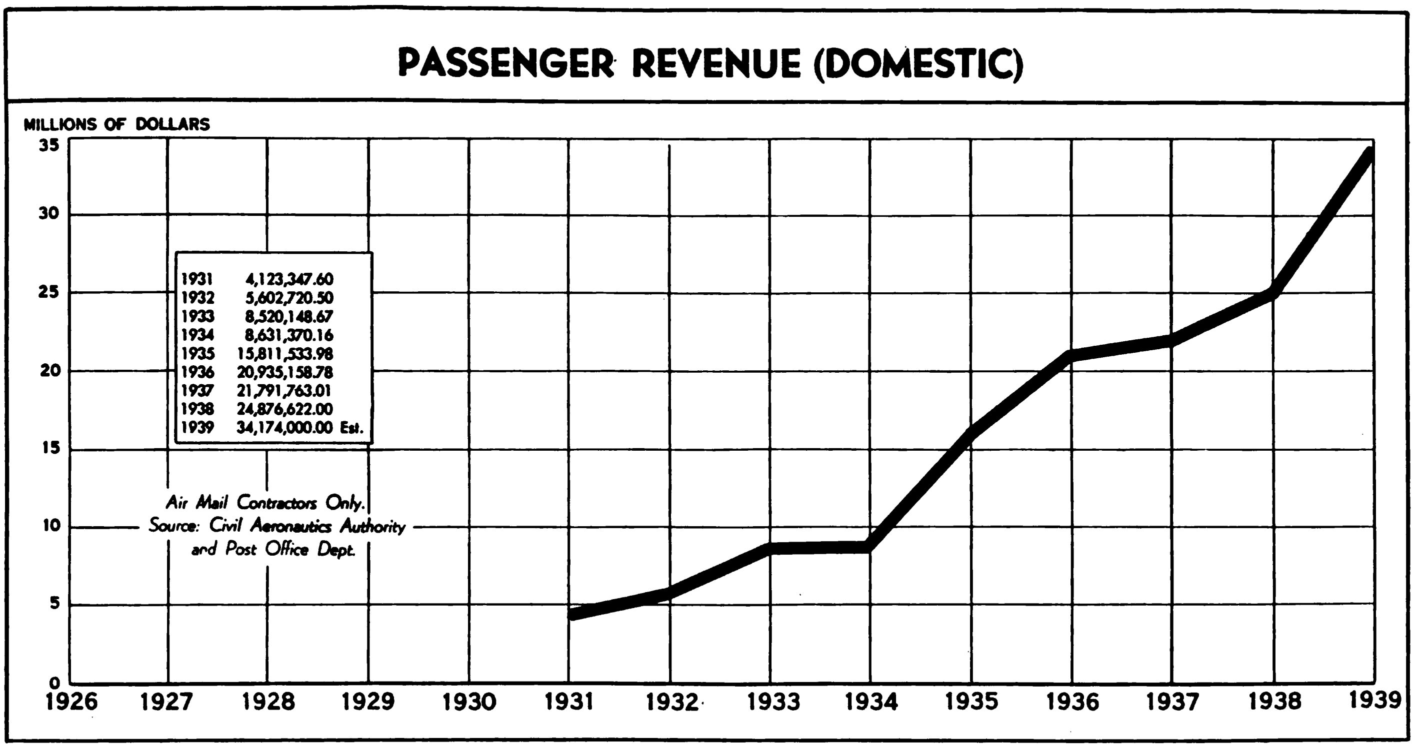


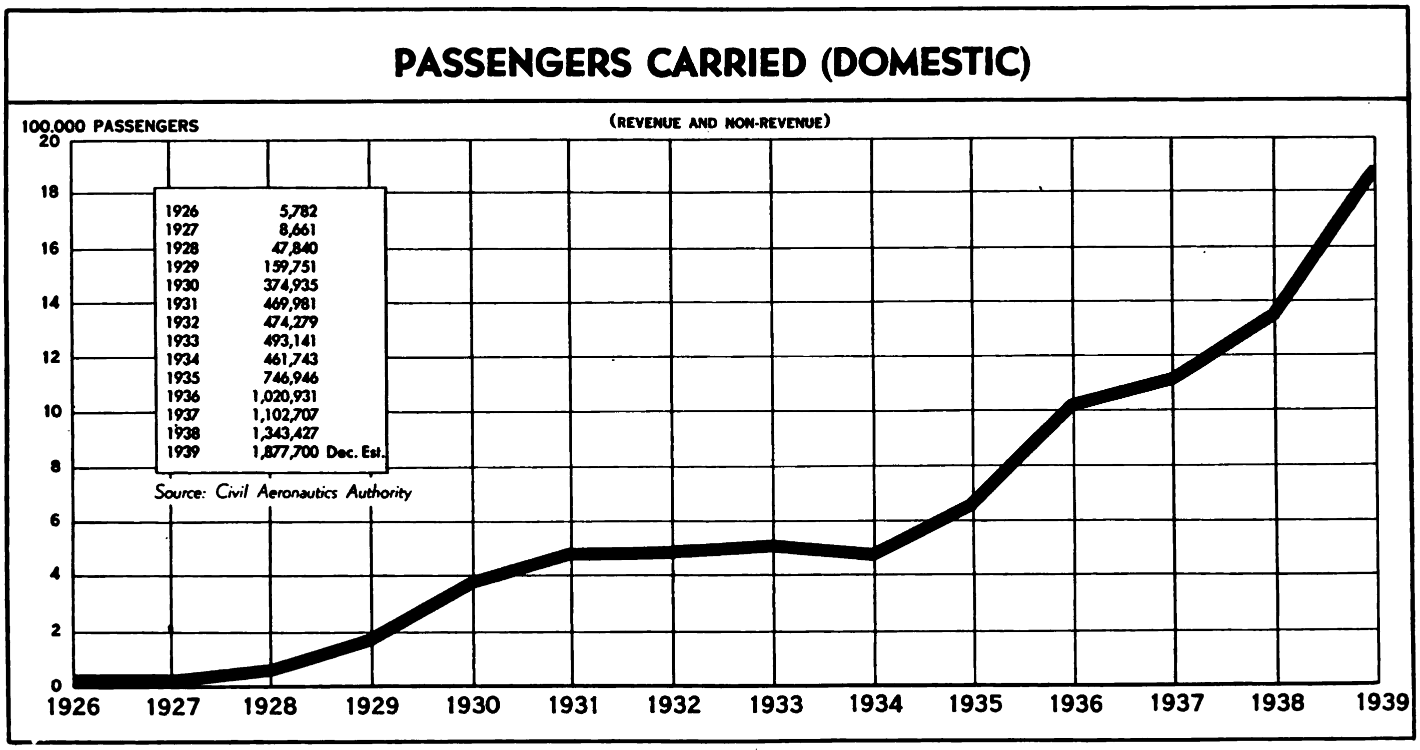
FIGURE 25.—Total Passenger Miles Flown



1931	4,123,347.60
1932	5,602,720.50
1933	8,520,148.67
1934	8,631,370.16
1935	15,811,533.98
1936	20,935,158.78
1937	21,791,763.01
1938	24,876,622.00
1939	34,174,000.00 Est.

Air Mail Contractors Only.
Source: Civil Aeronautics Authority
ard Post Office Dept.

FIGURE 26.—Passenger Revenue (Domestic)



1926	5,782
1927	8,661
1928	47,840
1929	159,751
1930	374,935
1931	469,981
1932	474,279
1933	493,141
1934	461,743
1935	746,946
1936	1,020,931
1937	1,102,707
1938	1,343,427
1939	1,877,700 Dec. Est.

Source: Civil Aeronautics Authority

FIGURE 27.—Passengers Carried (Domestic)

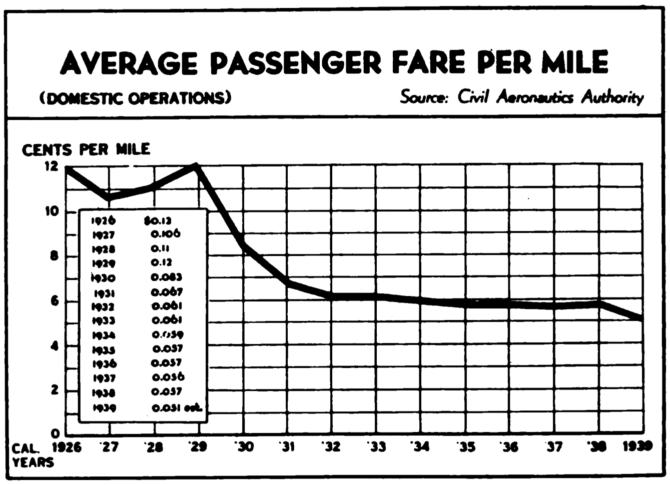


FIGURE 28.—Average Passenger Fare Per Mile

which exploit a new technology, but is very different in operation owing to the Government's paramount interest. An industry grows naturally from discovery as applications prove their utility. Examples can be found in chemistry, metallurgy, radio, and many sorts of special machinery. But in all of these fields, research is conducted by the industry for itself and is uncoordinated, except as a trade association or patent pool may assist members. Such private research is not given formal direction by its customers. On the other hand, the aeronautical industry, in its research, experiments, designing and testing, is led by the Government by three compelling strands.

First, the Government, through the Civil Aeronautics Authority, permits no civil airplane to be flown without technical inspection and a license as to air worthiness. For example, landing and take-off performance, as well as control and stability requirements may be changed from time to time by the C. A. A. as a result of experience (accidents perhaps) or as a result of National Advisory Committee for Aeronautics' research.

Secondly, the Army and Navy, as purchasers of aircraft in volume, set the trend of design by their specifications to bidders. No recent design competitions have failed to procure airplanes of superior performance as compared with the last competition. The Government's requirements are set somewhat ahead of the existing state of the art, and are based on the tactical needs of the services. Naturally, the industry is under compelling pressure to direct every effort through research and development work to meet the requirements of the competition. The Army might decide that performance will be judged at high altitude. Research men would then have to work on superchargers for engines, pressurized cabins for personnel, propellers geared for take-off at ground level, speed at altitude, and a host of other difficult problems. Similarly, the Navy might stress low landing speed on the deck of an aircraft carrier, and research men would be put to the study of high lift devices for wings and means to provide control at the stall. Likewise, tactical requirements may demand dive bombing, involving terrific speed and acceleration at the pull-out, and the research group will then have to study compressibility effects caused by high speed, and elastic problems of wing strength.

Thirdly, the Government leads and, to a large degree coordinates, research in the industry through the N. A. C. A. This Committee consists of 15 men appointed by the President under the authority of a 1915 Act of Congress. Nine members represent Government departments directly concerned with aeronautical progress and 6 are appointed from civil life but must be "acquainted with the needs of aeronautical science, either civil or military, or skilled in aeronautical engineering or its allied sciences." The members serve without compensation. For many years the chairman has been President Joseph S. Ames of Johns Hopkins University, recently relieved by Dr. Vannevar Bush, president of the Carnegie Institution of Washington. The Committee receives annual appropriations from the Congress "to supervise and direct the scientific study of the problems of flight, with a view to their practical solution." It makes an annual report to the Congress via the President. The annual appropriations, since the inauguration of the Committee, total about $25,000,000. (See table 2.)

TABLE 2.—*Appropriations of the National Advisory Committee for Aeronautics, 1915–40*

Fiscal year	General research purposes	Construction	Fiscal year	General research purposes	Construction
1915	$5,000		1930	$745,000	$763,000
1916	5,000		1931	896,000	435,000
1917	18,515	$69,000	1932	1,051,070	
1918	87,500	24,500	1933	915,000	
1919	167,000	38,000	1934	709,260	[1] 247,944
1920	170,200	4,800	1935	766,530	[1] 478,300
1921	184,450	15,550	1936	1,177,550	
1922	188,900	11,100	1937	1,177,550	1,367,000
1923	210,600	15,000	1938	1,380,850	353,000
1924	307,000		1939	1,500,000	200,000
1925	437,000	33,000	1939–40	223,980	2,140,000
1926	436,785	97,215	1940	1,849,020	2,330,980
1927	513,000				
1928	525,000	25,000	Total	16,261,520	8,653,389
1929	623,770	5,000			

[1] Allotment from Public Works Administration funds.

Research of the National Advisory Committee for Aeronautics

Research laboratories and staff are maintained at Langley Field, Va., on a site made available by the War Department. The Committee's research activity will be practically doubled by a new laboratory now being built at Moffett Field, Calif.

The N. A. C. A.'s work is primarily concerned with those fundamental problems of flight which are basic to the entire industry. Such research does not concern

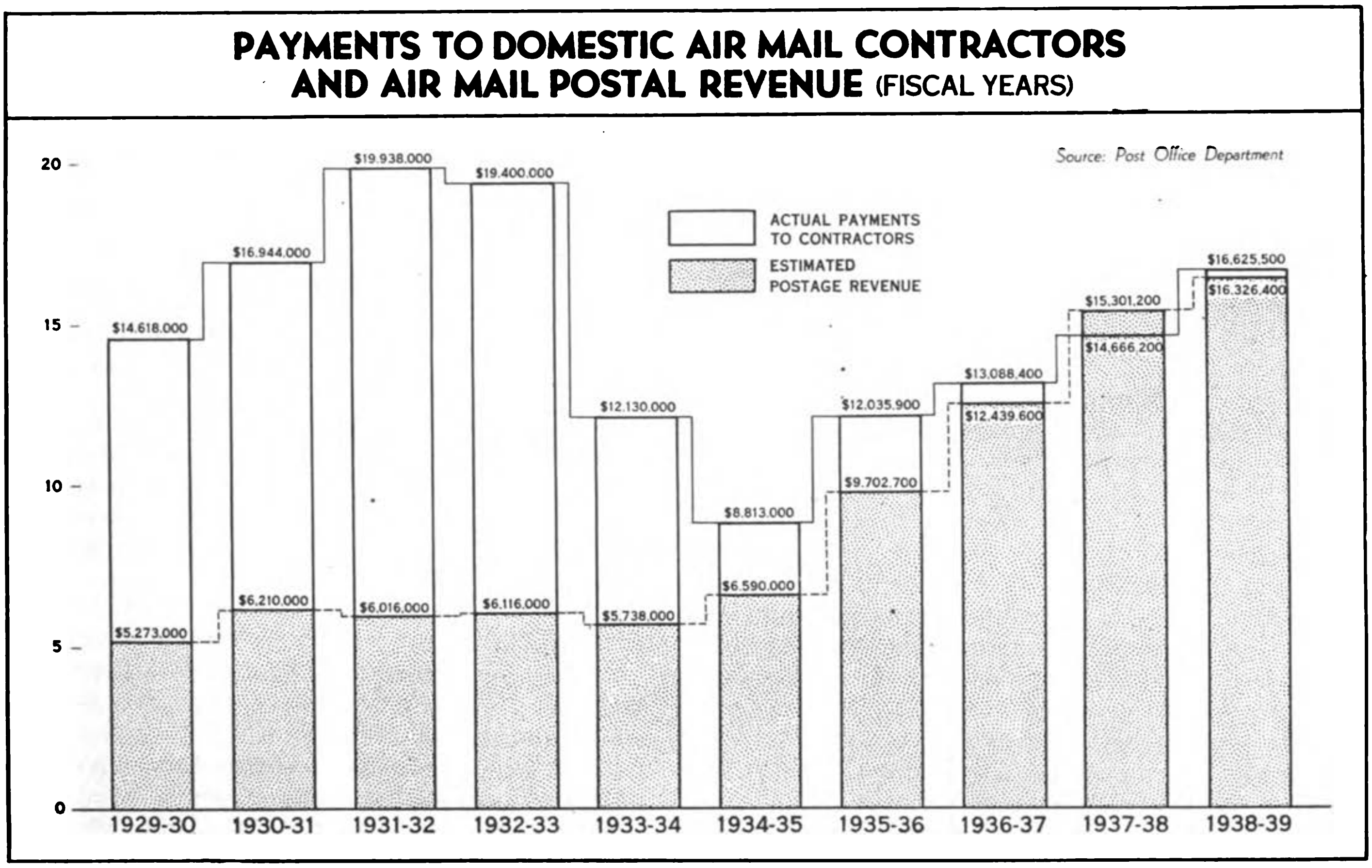


FIGURE 29.—Payments to Domestic Air Mail Contractors and Air Mail Postal Revenue

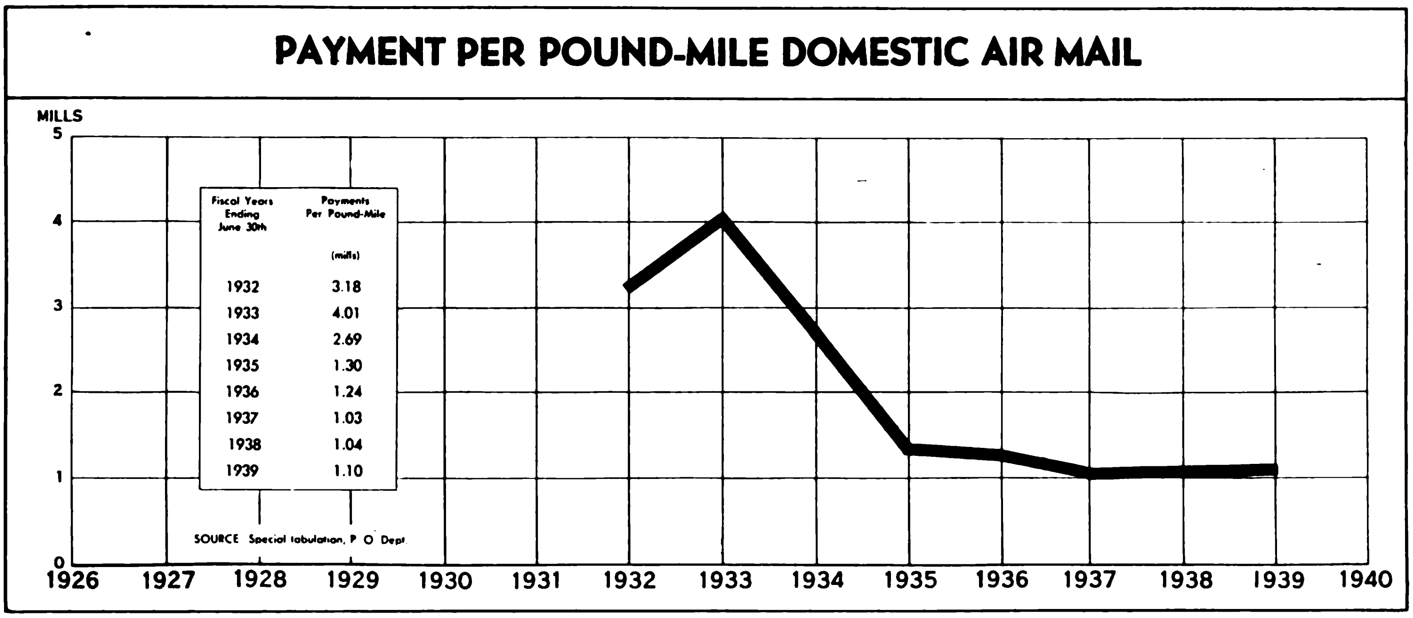


FIGURE 30.—Payment Per Pound-Mile Domestic Air Mail

a specific design of aircraft, nor is research conducted in fields of aeronautical science already adequately covered by the industry. For example, the Committee's own research does not deal with the metallurgy of aluminum and steel, refining of gasoline, and materials generally. Nor does it design engines, airplanes, nor accessories such as radio. These matters are known to be in good hands.

The Committee conducts scientific laboratory and free-flight research in the broad field of aerodynamic structures, and publishes results of value to designers affecting wing profiles and body forms, stability, and control, propellers, and methods for predicting airplane performance. It conducts theoretical and experimental research and, in general, seeks facts and principles where knowledge is lacking. This includes matters of structural strength, the combustion process and cooling of engines, and answers to many fundamental questions arising from the use of airplanes by the several Government agencies. Besides its own research results, the Committee makes available to the Army, Navy, Civil Aeronautics Authority, and the industry itself information obtained from abroad. For this purpose it maintained an Office of Aeronautical Intelligence and a full-time technical assistant in Europe stationed at the American Embassy in Paris.

The aeronautical industry is supplied with basic scientific information for its own design and research groups to apply. The results of N. A. C. A. research at Langley Field could not have been acquired by the industry independently, as the cost of the necessary equipment is far beyond the means of a young industry. It is largely by the intelligent application of N. A. C. A. aerodynamic findings by clever designers, that this vigorous industry has been able to advance so rapidly.

Naturally this information, when applied by foreign competitors, would produce equally beneficial results except that the more important results are not published until American industry has had an opportunity to study them. American designers, guided by their own research groups, seem to have been promptand skillful in the application of such results and have had, perhaps, greater confidence in the trustworthiness of the N. A. C. A. reports.

The N. A. C. A. conducts fundamental research at public expense, which, in effect, constitutes a substantial subsidy to the industry. Such a subsidy may be looked on as a small part of the cost of procuring rapid progress in an art vital to the national defense. Civil aeronautics benefits directly from the N. A. C. A. research, and our air transport system now leads the world in every aspect of good service.

The N. A. C. A. performs a coordinating function by means of subcommittees consisting of experts from the Government agencies and from various branches of the industry. Research projects are initiated or approved by appropriate subcommittees. Some projects are assigned, by contract, to university or other laboratories where special facilities or qualified personnel exist.

As a result of N. A. C. A. leadership, research in the industry has become applied. Through N. A. C. A. grants, most of the research in university laboratories is coordinated with that at Langley Field. Through Army and Navy procurement policy and Civil Aeronautics Authority regulatory functions, applied research in the industry is likewise directed along lines desired by the Federal Government.

We, therefore, have the unique example of an industry, exploiting a new field of technology, for which fundamental research is conducted for its benefit by the Government. Applied research is conducted by units of that industry, but under conditions that give the Government effective control.

The Institute of the Aeronautical Sciences

An important factor in stimulating research efforts of individuals was the formation in 1933 of the Institute of the Aeronautical Sciences. This organization of technical people includes specialists in aerodynamics, structures, engines, metallurgy, meteorology, radio, piloting, physiology and all of the sciences applicable to aeronautics. By means of national and regional meetings and by the publication of a monthly scientific journal, research problems are subjected to critical examination.

Society of Automotive Engineers

The Society of Automotive Engineers, primarily concerned with automotive engines and vehicles, has had a strong influence on the development of airplane engines and their special steels, fuels, lubricants, and standardized parts. It should be noted that the first publications dealing with the baffling of air-cooled cylinders and the cowl with trailing edge flaps appeared in the Society of Automotive Engineers' Journal.

The Daniel Guggenheim Fund for the Advancement of Aeronautics

In many sciences, important advances have been stimulated by the great foundations. In aeronautics the stimulus given by the late Daniel Guggenheim is still felt. In 1926, he established a fund of $2,500,000, later increased to $3,000,000, which was all expended by 1930 in aid of aeronautical progress. Substantial grants were made to eight universities for aeronautical laboratory buildings on condition that the university authorities maintain courses in aeronautical engineering, and in addition an airship institute was established. These Guggenheim schools have been extremely effective in supplying the engineering and research personnel needed for the expansion of the aeronautical industry between 1930 and 1940.

Projects started by the fund which have had a significant effect were: Research on ice formation (W. C. Geer); model airway weather service and introduction of air mass methods in meteorology (C. G. Rossby); blind-landing research (J. H. Doolittle); Safe Aircraft Competition ($100,000 prize to Curtiss Tanager); publication of the Encyclopedia of Aerodynamic Theory (W. F. Durand).

University Laboratories

The part of university research is an important though secondary one in the growth of the industry. University laboratories train the research workers who staff both Government and industrial research organizations. University laboratories dealing with problems of aerodynamics, radio, acoustics, physics, metallurgy, chemistry, electrical engineering, meteorology, structures, materials, fuels, lubricants, engines, etc., are frequently employed by the industry or by the Government to work on special projects. There are also, as would be expected, somewhat infrequent spontaneous contributions from university laboratories which prove of some importance. For example, university laboratories have made valuable contributions to current methods of analysis both in aerodynamics and structures, methods of vibration elimination, and instrumentation for the precise measurement of many phenomena from fuel detonation to propeller stresses.

In general, research in university laboratories is not so closely coordinated as is the case in Britain or Germany, but no doubt in time of war the N. A. C. A. could effect the necessary organization to utilize the available personnel and facilities effectively. The principal difficulty seems to lie in the fact that the university research worker does not often know the relative importance of the many problems of scientific interest, nor which problems are already being worked on elsewhere, and cannot be allowed to know the status of many problems of importance to the national defence.

Independent Workers

The university laboratories should remain free to work independently on research problems of their own selection without censorship or regimentation. Too close control, enforced in an effort to effect close coordination, can result in such regimentation that a research project may be suppressed completely. If the coordinating office be prejudiced or lacking in imagination, progress can be greatly delayed. The air-cooled engine, when first proposed, was of no interest to one branch of the Government, but, fortunately, another branch insisted on its development. Individual workers, in the aeronautic field as in others, have been the source of many good ideas. We need only to recall the fundamental work of Lanchester or Bryan in England and of Prandtl in Germany. In this country, especially, we should never forget that the airplane itself came from two completely independent persons, the Wright brothers.

In more recent times organized research has built up the basic information from which inventions develop. The practice of the N. A. C. A. in publishing its research results makes a great store of knowledge available not only to the technical groups in the industry but also to the university laboratory and the individual scientist.

Conclusion

Government research is largely responsible for remarkable progress in the development of the airplane, but it alone could not have made the improvements from which a healthy industry has developed. Basic research results had first to be extended and applied by the research groups in the industry, incorporated in designs, and tested in competition with the existing art.

While Government research and requirements have dominated the growth of the industry, in its general effects the Government's activity has been wholesome, probably because the industry was left with plenty to do for itself, and also because airplanes and engines are not designed by the Government. There is no Government competition with industry. The Government sets standards of quality and offers help in the form of research information toward attaining such standards, and money prizes in the form of purchase orders for the survivors of competition.

By a combination of circumstances, but principally because of the importance of improved airplanes to the national defense, the function of research in the aeronautical industry has been paramount. The lesson seems to be that where research is so placed, technical progress is rapid and commercial success follows.

Evidence of sound progress is given by the downward trend of rates charged for service rendered as shown on figures 28 and 29. Passenger fares have dropped from 12 to 5 cents per mile, while the rates paid by the Post Office for the carriage of air mail dropped 75 percent. The result is a profitable industry, able to create further improvements and more business.

Progress from Improvements

To seek the cause of the rapid progress of the aeronautical industry it is only necessary to trace the improvement of the airplane in performance and utility. The obvious steps in this improvement have sometimes been abrupt, but apparent periods of stagnation merely indicate times when research results are accumulating while application is blocked at some point. At any one time there is no lack of good ideas but the ideas may be impractical until advances have been made in related fields of science and technology. A technical advance comes only when the time is ripe. High-compression engines could not be adopted until high-octane fuel was commercially available. Landing gears could not be retraced until thick cantilever wings were in use, and it was not worth-while to retract them until the speed of flight became great enough to put a premium on saving the drag of such exposed parts in spite of the increased weight and cost of the retracting mechanism.

The airplane flies in accordance with aerodynamic principles which govern the phenomena of air flow. Advances in aerodynamic knowledge set the trend of design and stimulate the adoption of nonaerodynamic features, which in themselves may lead to further improvements in performance. Likewise, the engine and propeller are fundamental to the mechanics of flight and improvements in the power plant are reflected in improved airplane performance. Piloting is also an essential element, and improvements in aids to navigation, in weather forecasting, and in radio have been important stimulants to the growth of the industry.

The effect of improvements arising as a result of research is easily traced in the growth of air transport from a daytime air-mail service in 1924 to the overnight transcontinental sleeper service we have today. For the year 1939 the air-transport planes, on domestic air routes only, flew approximately 80,000,000 miles. This development in only 15 years could never have happened unless the public patronized the planes with increasing confidence as the service improved.

Dr. Edward Warner, in his Cabot Lecture of 1938 at Norwich University, noted five major steps in air transport's technical development:

1925–29, increased wing loading;
1925–26, multiengined airplanes;
1929–33, N. A. C. A. cowling;
1930–36, high-octane fuel;
1933–34, controllable-pitch propeller.

Each of these steps was marked by the general adoption of a specific design feature which had a great effect in improving the performance of the airplane and consequently the service offered by the common carriers. None of these features appeared at a single stroke, but resulted from years of research and experiment with a few false starts and failures.

To consider these five steps in order, let us inquire as to increased wing loading. The weight per square foot carried by the wing increased only from about 8 pounds in 1918 to 10 pounds by 1925. Smaller wings for the same weight of airplane mean more speed, less dead weight, and a smoother ride. The wing loading for a given safe landing speed increased after 1925 very slowly, but in 1929 the Guggenheim prize was won by a machine using wing flaps temporarily to increase the lift when landing. By 1933 such flaps were in general use on air transports, permitting a wing loading of 15 pounds per square foot. Research had, in the meantime, shown how to design them and to predict their effect. Wing loading has since doubled with a corresponding reduction in wing area.

The second major improvement in air transport planes came with the introduction about 1925 of Ford, Fokker, and Junkers multiengined planes. Multiengined bombers had been used in the First World War but were notoriously inefficient, and needed all of their engines to keep in the air. By 1935, however, improved engines and aerodynamic qualities permitted these new transports to fly with one engine stopped. Results of research allowed the use of this design feature that greatly increased safety and, at the same time, made it possible to build larger airplanes to carry greater loads with lower cost. With the general adoption of multiengined transports, the industry expanded to handle the increased traffic that resulted from reduced fear of a forced landing. No passengers are now carried on our air lines in single-engined machines.

The third major step in improvement and in the industry's growth had its origin in the construction in 1927 by the N. A. C. A. of a wind tunnel large enough to test a full-scale airplane with its regular engine and propeller. With this equipment, it was discovered that a very large part of the head resistance of the airplane was due to the radial air-cooled engine. The engine had to be exposed to the wind to keep it cool, but in such a position, the air flow was spoiled for part of the airplane behind it. Systematic research disclosed means to smooth out the flow by means of a cowling to lead air to and away from the cooling fins of the engine. The cowl devised by Fred E. Weick, now known as the N. A. C. A. cowl, reduced engine drag 75 percent. This important saving permitted a sharp increase in speed and economy of transport planes. By 1933 the N. A. C. A. cowl and radial engines were standard on all United States air lines, as well as in military service. It is estimated that the fuel bill in 1939 for United States domestic air lines was about $5,000,000 and for the Army and Navy at least $6,250,000. Removing the N. A. C. A. cowls from a typical transport plane or bomber would increase the drag approximately 30 percent or reduce the speed 10 percent. To maintain the same speed, the national fuel bill would be increased $3,375,000. This sum represents an annual recovery of many times the cost of the research.

The N. A. C. A. cowl when first applied to single-engine airplanes increased speed approximately 15 percent, but when applied to the three-engined airplanes of that day resulted in no increase in speed. This led to a fundamental investigation by the N. A. C. A. to determine the cause and to find the remedy. By a comprehensive survey of the net efficiencies of various engine nacelle locations, the optimum position in the wing was found. This N. A. C. A. engine location principle, together with other refinements, had a revolutionary effect on military and commercial aviation the world over. It changed military aviation tactics, made long-range bombers possible, and forced the development of higher speed pursuit planes. In the commercial field it permitted the speeding up of cruising schedules on the air lines from 120 miles per hour of the Fords to the 180 miles per hour of the new Douglas planes. The overnight transcontinental run became possible and the air lines vastly increased their appeal to the public. Even in the midst of the depression, air line traffic boomed.

The fourth great change in air-transport equipment came about without benefit of Government research. It has its beginning during the First World War when the General Motors Research Corporation and the Cooperative Fuel Research Committee (Society of Automotive Engineers and the American Petroleum Institute) undertook research on the knocking of automobile engines. This research evolved a method of measuring knock qualities of a fuel by "octane number." Thomas Midgely found substances that would raise the octane rating of gasoline and, in particular, tetraethyl lead. The use of high octane fuel permitted higher compression in engines, leading in turn to greater power for the same cylinder volume and better fuel economy. The air-transport industry did not benefit from the results of this most important research until 1933 when leaded fuel was commercially available as well as engines designed to use it. Since then the oil industry has continued to raise the octane rating of aviation gasoline and engine designers have correspondingly increased the specific output of their engines.

The technical improvement in both fuel and engines has come from research by the industry, but high-output engines and high-octane gasoline did not appear on the airlines until the Army and Navy had established the practicability of the combination and, by volume orders, had made commercially available what was at first only experimental.

The fifth major improvement in the airplane also came from the industry. The idea of a controllable pitch propeller is to have a low pitch for take-off which can be changed to a high pitch when high speed is desired. The idea is not new, but the mechanical difficulties are formidable. The desire for such a solution did not become pressing until 1932 when it was clear that pay loads could not be raised to an economical level without better take-off power. When the controllable-pitch propeller was really needed, it was found that a firm in the industry, which had been conducting research for many years, had a practical type ready for application. Since 1933 Hamilton-Standard controllable-pitch propellers, following F. W. Caldwell's designs, have been standard equipment on all United States airlines. The improved performance due to landing flaps, N. A. C. A. cowls, high-octane fuel, high-output engines, and controllable-pitch propellers all came at about the same time. Between 1935 and 1938, schedules were speeded up, frequency was increased, and fares were lowered, and in 1939 airlines began to make money.

Many other improvements beside these five major ones have become possible, directly, as a result of research, and indirectly, as a result of manufacturing profits diverted to support research. A complete survey and appraisal of research results and their sources would be too long to record, but the nature of a number of significant improvements is indicated in the last part of this article.

While improvement in the airplane itself is the fundamental cause of the growth of the manufacturing business, air transport lines and the military and naval air forces, it must not be forgotten that other factors are essential. In air transport, for example, the carriage last year of more than 2,000,000 passengers in safety and comfort required careful planning and sound policies by both the regulatory authority and by management. Also, we have had new facilities on airways and airports, with marked progress in applied meteorology and in radio communications. The radio equipment in one airliner today costs more than did an entire airplane a few years ago. One airline maintains a chain of radio stations of greater number than any commercial broadcasting network. Progress in aeronautics depends on progress in many arts and sciences and on an alert management working within a framework of wise regulation.

Research Results Leading to Improvements

General Aerodynamics

In 1901 the Wright Brothers built a small wind tunnel with which they determined, by systematic experiment, the aerodynamic effects of wing curvature, plan form, aspect ratio, and gap-chord ratio. These studies are significant in view of later research which has found only one other basic variable of wing design, namely thickness. The Wrights also checked by means of a glider the scale effect involved in converting model data to apply to full-scale wings. From their research data, the first successful airplane was designed and built. During the next 10 years others took up wind-tunnel experiments, but results were not of major importance. In general, designers tested new ideas by trial flights or by *ad hoc* wind-tunnel tests.

During the First World War, experimental aerodynamics expanded rapidly, but the pressure for routine testing of current designs side tracked systematic research. The momentum of the war period carried on for several years, but by 1925 the airplane, although refined as a result of many minor improvements, ceased to progress by customary cut-and-try methods. The airplane designer now needed fundamental guidance in applied aerodynamics. He received it in full measure from the National Advisory Committee for Aeronautics whose laboratories at Langley Field, started in 1917, had been steadily publishing systematic wind tunnel research data. Some of their more valuable contributions are listed below:

(1) The determination of the aerodynamic loadings on wing, tail, and control surfaces in steady flight and in maneuvers, and pressure-distribution data led to more economical structural designs. Designers became conscious of the relative costs of drag and structural weight. They were provided with criteria and methods of analysis from which they could proceed with confidence. The wired biplane was soon replaced by the cantilever monoplane.

(2) In the early years of the airplane, wing profiles were drawn up arbitrarily by their designers. The N. A. C. A. published characteristics for a codified and classified series of systematic variations. Its 2,300 series has been notably successful and has had world wide application.

(3) High-lift devices: The trailing edge flap, the slotted flap, and its variants were invented by individuals in the industry, but the N. A. C. A. has been of great assistance in evaluating the effectiveness of such devices and in publishing aerodynamic data regarding their operation. Such devices are now in general use.

(4) Low-speed control: The N. A. C. A. data on flow separation and stalling led to the design of improved methods of control.

(5) Spinning: Special laboratory and mathematical analyses by the N. A. C. A. of this dangerous fault in an airplane have given a better understanding of the mechanics of the motion and the cure for it. Practical solutions are made by the airplane designer (vertical tail-surface location).

(6) Flutter: Again special laboratory and mathematical analyses by the N. A. C. A. have given a rational theory of the mechanics of wing flutter as a foundation for the designer's practical solution (mass balancing of control surfaces).

(7) Rotating wings: The N. A. C. A. has supplied the basic theory and the experimental coefficients for designers of helicopters, autogyros, and other rotating wing craft. The inventions have come from individuals, the theory from the laboratory.

(8) Full-scale testing: N. A. C. A. work with airplanes in flight, equipped with complete instrumentation to record behavior, has given an engineering foundation to performance estimation. In particular, flight check on spinning-tunnel results, full-scale measurement of profile drag by the use of the wake comb, low-friction laminar-flow wings, aileron-control studies, and Reynolds Number effects have supplied fundamental data and methods to designers.

(9) Tank testing: The design of flying boats is based on model tests in the towing tank. American flying boats now enjoy a superiority that can be attributed in large part to the research work of the tank at Langley Field.

(10) Skin friction: The theoretical analysis of skin friction (Prandtl and von Karman) has been developing for more than 30 years, but its practical applications have not as yet been impressive. Langley Field wind-tunnel work, however, has given important guidance to designers by evaluating the cost in drag of roughness of surface. Research conclusions have recently stimulated designers to the introduction of flush riveting and new standards of surface smoothness for high speed airplanes.

(11) Compressibility: Progress toward higher speeds, approaching the velocity of sound where the compressibility of the air changes the flow pattern, depends on specialized wind tunnel equipment. Research of the N. A. C. A. has given designers information as to sharp-nosed wing and propeller profiles, easier body forms, and other data vital to the design of high-speed airplanes.

(12) Engine cooling: The N. A. C. A., by means of tests in its large-scale wind tunnels, showed the industry how to enclose air-cooled engines with minimum drag. Progress in this avenue of research is continuing with the promise of further substantial gains in speed and economy.

(13) Engine location: Systematic wind-tunnel research by the N. A. C. A. on the best location for engines of multiengined airplanes has had the effect of standardizing the monoplane wing with two or four engines in the leading edge. This contribution to practical design originated in the laboratory.

(14) Propellers: By means of systematic studies of model propeller performance, the aerodynamic design of airplane propellers has been standardized. The mechanical design of propellers, notably the variable-pitch constant-speed feature, was evolved by the industry. The N. A. C. A. contribution is to the prediction of performance.

Airplane Design

(1) Multiengined airplanes: The desire to build larger airplanes led the industry to undertake multiengined designs as soon as the state of the art permitted. The initiative lay with the industry.

(2) Steel construction: Beginning with Fokker's welded-mild-steel-tube fuselage, the industry quickly adopted alloy tubing when it became available in the automotive industry.

(3) Stressed-skin construction: When increased speeds made fabric covered frameworks inadequate to carry high local air loads, the industry adopted metal coverings. Designers had to use this skin as a stress-carrying element, but had no rules to guide them. Research at the N. A. C. A., National Bureau of Standards, Massachusetts Institute of Technology, and California Institute of Technology provided criteria for allowable stresses in thin structural elements. It may be said that the heavy all-metal monoplane wings would not have been used until high wing loadings, cowled engines, retracted landing gears, and high speeds were current. Also, such wings could not be designed with confidence until research data were available.

(4) Plastic construction: It is too early to evaluate the effect of reinforced plastics in stressed-skin airplane construction, but the advantages are obvious and research in the industry is very active. One may predict with confidence that a successful application will be made.

(5) Cantilever monoplane: This development was stimulated by N. A. C. A. aerodynamic research which showed its advantages and showed that a thick wing need not be inefficient. The actual construction was undertaken by the industry when duralumin became available.

(6) Retractable landing gear: Increased speed as a result of aerodynamic refinement made a retracting landing gear worth-while. The idea was embodied in a racing airplane as early as 1922, but was then considered impractical. With thick cantilever monoplane wings, retracting the wheels into the wings became relatively simple. An important gain in speed resulted. A further development by the industry is a mechanism by which the landing wheels on cantilever struts are rotated during retraction so as to fit into the thin wings of a pursuit type airplane.

(7) Tricycle landing gear: The placing of a castering wheel in advance of the main landing wheels is not new but has been revived for modern transports to avoid instability when running on the ground and to facilitate the use of the new "blind landing" system. The tricycle gear is not in itself a research result, but its readoption was the result of N. A. C. A. research indicating its fundamental advantages, and was necessary to take advantage of other advances in the art which require a new landing technique.

(8) Hydraulic retraction: Research in the industry has developed a hydraulic shock strut that may also be used to retract the landing wheels. This device has made it possible to build "amphibians" without excessive weight penalty.

(9) Retracting wing floats: Similarly the industry has developed a retracting wing float for high-speed flying boats.

(10) Wheel brakes: Wheel brakes independently operable were experimented with and their advantages for maneuvering airplanes on the ground and for shortening the landing run were presented by Porter H. Adams in 1915. They were introduced in industry in 1929. The gain in operation efficiency for air transport service is important.

Engines

(1) Air-cooled radial: The greatest factor in the improvement of American airplanes in the 1920's is without doubt the air-cooled engine, originally developed by the industry with Navy backing. Such a light, efficient, and reliable power plant could be produced only when research and development work in many fields had progressed to the point of useful application. In that connection may be mentioned light-alloy castings, exhaust-valve steel, salt-cooled valve design, special bearing metals and lubricants, light reduction gears, special-precision machine tools, heat-transfer data, high-output cylinder design, improved spark plugs, improved steel forgings, etc.

(2) Twin-row air-cooled radial: The output of the air-cooled engine has recently been greatly increased by the twin row without sensible increase of frontal area. Such engines are made possible by more effective baffling and cooling, vibration elimination, better control of carburetion, and in general by an enormous amount of research and testing by the industry.

(3) Liquid-cooled engines: The successful development in this country of high-output liquid-cooled engines similar to those in use abroad for high-speed pursuit airplanes is a notable achievement. This type of engine has been produced by the automotive industry through its own research, with Army backing.

(4) Dynamic damping: The practice of dynamic damping of crankshaft vibration has greatly improved engine performance and safety. A widely used practical solution is based on theoretical work in a university laboratory.

(5) Dynamic suspension: The current method of mounting engines, by so positioning the angular bracing with relation to the center of mass of the engine that engine vibration has little disturbing effect on the main

structure, is also based on theoretical work in a university.

Propellers

(1) Metal propellers: The use of forged duralumin blades dates from 1925 when the industry developed from Albert Sylvanus Reed's original invention. More recently, research efforts in the industry are being directed toward hollow duralumin or steel blades, or the use of magnesium or reinforced-plastic material to avoid increasing weight for the greater power required by the new engines.

(2) Variable pitch: Metal propeller blades with variable pitch, automatically governed, and feathering, have been developed by the industry on its own initiative, as mentioned previously.

(3) Stress measurement: The design of metal propellers for modern engines required exact knowledge of the distribution of stress in the blade under operating conditions. Methods for making such measurements have been developed by the industry in connection with a university laboratory.

Materials

(1) Duralumin: This strong alloy of aluminum was developed and made generally available by the Aluminum Company of America after extensive research undertaken in connection with the Navy's airship program.

(2) Stainless steel: This remarkable material and means to spot weld it are available in the metallurgical industry. It may become important as airplanes increase in size.

(3) Magnesium: As a result of research in the metallurgical industry, alloys of magnesium are becoming of increasing use, especially for engine parts and castings.

(4) Extruded sections: The industry has developed a comprehensive set of standard structural shapes for extrusion with consequent gain in efficiency and reduced cost of manufacture. Research by the industry has established the stability and strength properties of such sections.

(5) Plastics: Many uses for plastics are being found; in particular, the flexible transparent plastics which replace glass. Research is conducted by the industry and by the government.

Accessories

(1) Soundproofing: The industry has evolved, through its own research, effective methods and materials for soundproofing airplane cabins. The improved passenger comfort has done a great deal to popularize air travel.

(2) Fuel tanks: Research by the industry has produced safe riveted and welded fuel tanks and tanks lined with synthetic rubber.

(3) Supercharges: Both exhaust-driven and gear-driven superchargers have been developed by the industry to boost the power of engines at altitude. As a result, air transport planes can fly high enough to avoid most of the bad weather.

(4) Gyro pilot: First introduced by Sperry in 1931, the automatic gyro pilot has revised flying technique as regards large airplanes and has contributed greatly to safety in flight.

(5) Radio: Direction finders, radio beacons, two-way radio telephone sets, and other radio aids to navigation have had an important effect on the growth of air lines. Without radio, operations could not be conducted with safety in bad weather. Radio equipment is the result of research in the radio industry.

(6) Gyro compass, sensitive altimeter, turn and bank indicator, and other flight instruments have been developed by the industry. They are indispensable.

(7) De-icing equipment: To permit flight under icing conditions, the industry developed de-icing equipment of very effective nature. Such equipment is essential to the maintenance of schedules on northern routes in winter.

(8) Blind-landing equipment: Current research by the industry under the direction of the Civil Aeronautics Authority is developing radio means for guiding an airplane to a landing in times of no visibility. Blind-landing research was initiated in 1926 by the Guggenheim Fund, and the first demonstration made by Maj. James H. Doolittle, September 24, 1929. It is expected that the next important improvement in air transport service awaits the successful reduction to practice of means now being experimented with.

Military and Naval Research

Research within the Army and Navy deals primarily with the adaptation of the airplane to service requirements and the development of armament and other special equipment. For this purpose both the Army and Navy maintain extensive research facilities and scientific staffs.

Special equipment is developed within the service, with N. A. C. A. advice when requested, and is usually built by the industry. Examples: Navigating instruments, machine guns, cannon and mounts, bombs, bomb sights, torpedoes, catapults, arresting gear, hoisting gear, special radio and signaling apparatus, photographic and mapping equipment.

Just as certain improvements in the airplane leading to greater speed, pay load and economy have resulted in the growth of an air transport industry, so also have the same improvements resulted in the growth of the military and naval air forces. The relative importance of an air force depends on the performance of its airplanes. When bomb loads can be increased, bombers become more useful and more are built, together with more pursuit planes.

The Navy has developed the airplane carrier and the catapult in order to equip the fleet with airplanes which have become necessary both for observation and as a striking force. Improvements in the airplane are reflected in the greater role assigned by the fleet to its air arm.

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Engine development may be followed through the *Proceedings and Journal of the Society of Automotive Engineers*. "The Internal Combustion Engine" by Taylor and Taylor (International Textbook Company, Scranton, Pa.) contains a complete bibliography.

Aerodynamic research results are given in the comprehensive six-volume work, "Aerodynamic Theory," W. F. Durand, Editor-in-Chief, published by Springer (Berlin) under a grant of the Guggenheim Fund for the Advancement of Aeronautics. The contributions of the many authors are fully documented.

SECTION III

2. RESEARCH IN THE PETROLEUM INDUSTRY

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ABSTRACT

Research has played an important part in the period of the most rapid growth of the petroleum industry. It has been indispensable to industry in meeting technical problems arising from day to day. In production, research has put on a scientific basis the locating of oil reserves and made possible drilling to unprecedented depths and recovering the maximum yield of oil. In manufacture, research has brought fuels and lubricants to their present state of perfection, and enabled refiners to supply the changing demands for individual products with a minimum of loss through byproducts of lesser value. The successful coordination of the various phases of technology, geology, metallurgy, chemical engineering, etc., in the past, promises to continue to assist in the growth of the petroleum industry by overcoming technical obstacles as they are encountered, and by opening up new fields of development.

The eventual beneficiary of all the contributions of research to the petroleum industry is the public as a whole. Improved methods involved in the field of oil production not only facilitate obtaining oil from the ground, but have the effect of conserving petroleum resources. Thus, better prospecting and better oil recovery serve to expand oil reserves, and known reserves instead of diminishing are growing from year to year. Improved refining methods applied to automotive fuels reduce the cost of gasoline while improving its performance characteristics; and improved lubricant refining methods result in similar benefits to the users. Improvements in refining apply in the same way to all other petroleum products. Moreover, improved refining methods, besides bettering product quality, also effect a conservation of products. For example, cracking permits of producing increasing percentages of gasoline from crude to meet the proportionately larger demand for gasoline than for the other products. Other processes, such as polymerization, hydrogenation, alkylation, etc., likewise permit of converting the less useful to the more useful products. And finally, the conversion of hydrocarbons to other types of chemical compounds insures that every constituent of petroleum will come to some useful end.

The petroleum industry is directly a major factor in industrial employment. The extent of its effect on employment indirectly, through related industries, can only be estimated, but is undoubtedly tremendous. The growth of the industry to its present proportions has all occurred within a relatively short space of time. This growth has paralleled and can largely be attributed to the continuous expansion of research in the industry. And the uniform growth of industry as a whole, is evidence of the widespread distribution of the fruits of research throughout the industry. On the basis of accomplishments to date, research under the present policies in the petroleum industry is stimulating the manufacture with lower losses of better products at lower costs.

Introduction

The inception of the petroleum industry with the successful drilling of the first oil wells some 80 years ago, was followed by a gradual and continuous growth which at the turn of the century had led to an annual domestic crude oil production of 63,621,000 barrels. Impressive as this may have appeared to an earlier generation, it now seems a rather modest growth compared to the subsequent expansion which has increased this figure approximately twenty-fold to 1,264,256,000 barrels in 1939. The importance of this development—which may be followed from the upper curve in figure 32—can best be appreciated from the fact that it has brought the petroleum industry up to the rank of the fifth largest industry in the country.

From the standpoint of the contribution of research, we here have the example of an industry that from a comparatively modest start has grown to large size within a short span of years. During a large portion of its early history, the prospector played a dominant role in the petroleum industry. This was the period of exploration and empire building. With the growing

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[*] The authors wish to express their thanks to Mr. R. G. Sloane for his diligent efforts in compiling and organizing the work presented herewith.

importance of refinery operations, the engineer came into prominence; this was at a time somewhat before the advent of the automobile, when more emphasis was being placed on construction and operation than on process development. Problems in plant control called for the aid of the chemist. But the chief concerns of the refinery chemist of those days were the smooth operation of existing equipment and the maintenance of product quality.

The recourse to organized research has come largely during the last two decades, through the wholehearted application of chemical engineering methods and the establishment of well integrated research staffs. With the organization of research, important technical developments quickly followed. The automobile and aviation industries as we know them today could never have materialized had it not been for the contributions made by the technical workers in the petroleum field. Moreover, to provide an adequate supply of fuels and lubricants, meeting more and more exacting requirements with respect to quality and performance, it has been necessary to call upon the closest cooperation between research workers in many fields, such as engineering, metallurgy, geology, chemical engineering, and chemistry. Although the greatest proportion of research activities has been concerned with problems arising with the growth of the automotive industries, the accomplishment of petroleum research extends far beyond this field; it has had a pronounced effect on the development of a variety of products ranging from industrial fuels and lubricants, domestic fuels and road-building materials to an ever increasing line of specialty products and chemical derivatives.

So completely has the petroleum industry turned to research for guidance that today the industry stands as one of the leading employers of technically trained personnel. Through the aid of research it has become one of the pioneers in the current trend to produce better things at lower cost, so as to enable industry to pay higher wages and to make its products available to the greatest number of people.

In reviewing the methods and accomplishments of petroleum research, one cannot help being impressed with their consequences in the larger field of our country's social economy. The present paper, therefore, while citing specific technical achievements will also attempt to analyze their particular implications as they affect the national life.

Technical Problems Involved

Space considerations make it impossible to present more than a small fraction of the contributions made by research in the solution of the technical problems that have been encountered in the development of the petro-

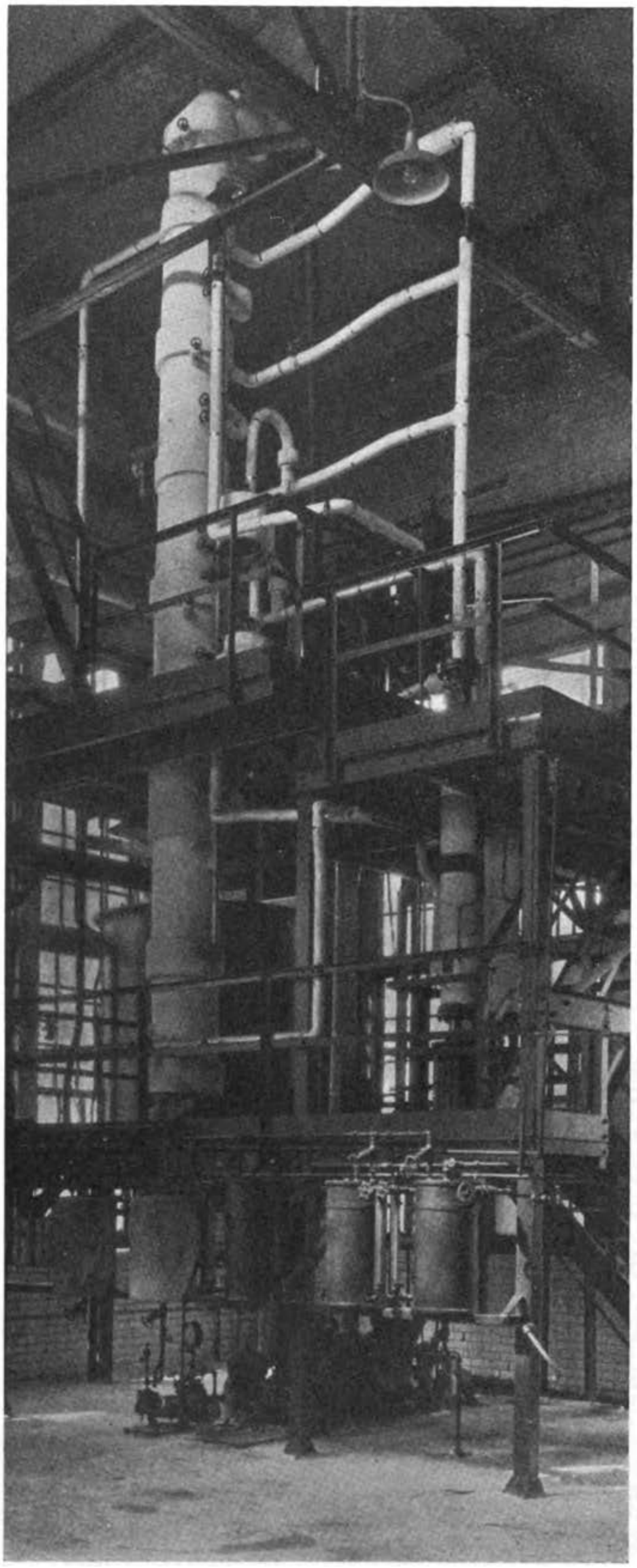

FIGURE 31.—Model of Pipe Still Used in Development and Improvement of Processes, Standard Oil Development Company, Elizabeth, New Jersey

leum industry as we know it today. However, the following illustrations will serve to bring out many of the more significant phases of the subject.

Production

The initial problems in oil production were primarily of a specialized engineering nature. Early wells were relatively shallow, but the perfection of methods for drilling to greater depths was soon required. In addition, it became necessary to improve methods of prospecting. Well drilling was too costly a process to warrant the selection of drilling sites with a divining rod. At the present time, with the assistance of geology, geophysics, and more recently geochemistry, prospecting has attained a remarkably high degree of perfection. Intensive research in these sciences has led to the development of new methods and tools which have played a major role in the new discoveries that have made it possible to supply our demands for crude oil, and leave us today with an estimated underground reserve of some 19,000,000,000 barrels. Aside from aiding in the location of new oil deposits, research on oil production—applying principles of chemical engineering operations—has also resulted in greater efficiency and economy in oil recovery by such means as more efficient well spacing, controlled flow, gas repressuring, acidification, and water flooding. These improvements in the efficiency of recovering oil from the ground have in recent years contributed materially toward increasing the net reserves.

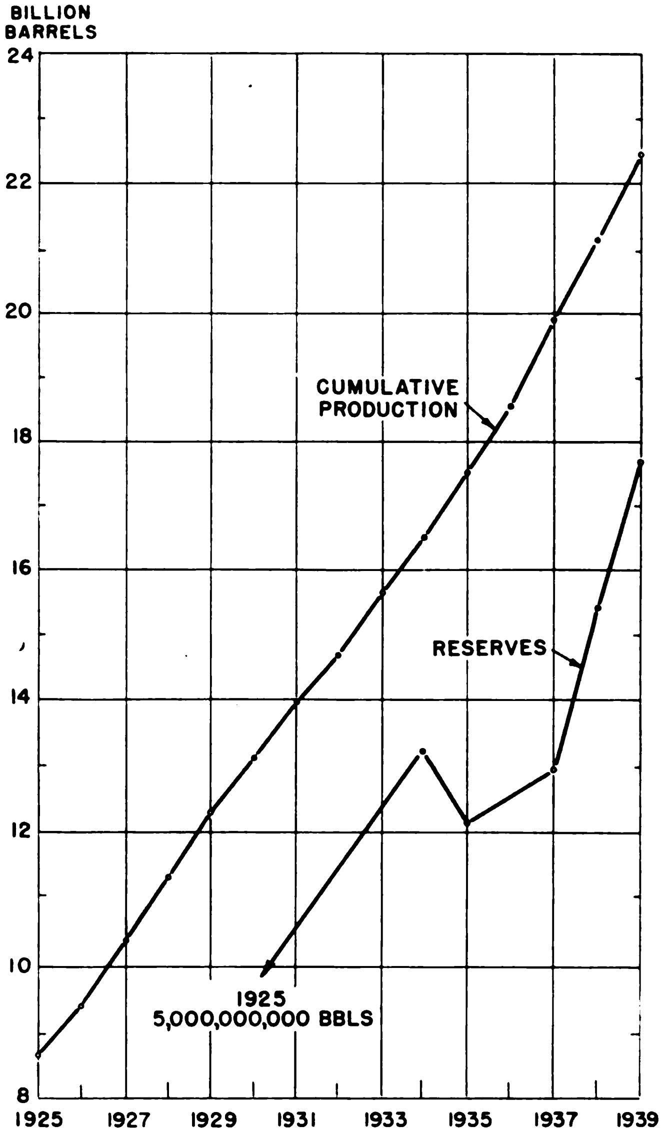

FIGURE 32.—Production and Reserves of Crude Oil in the United States, 1925–39

Of considerable importance as a conservation measure is the improvement in locating oil deposits. Indications of this improvement are to be found in the fact that the petroleum industry has been able to maintain the number of dry holes among completed wells at approximately the same percentage over a number of years, in spite of the less obvious surface signs of oil as drillings to greater depths become necessary. The percentages of wells which found oil and gas, and which were dry over a number of years in the United States, are tabulated below:

TABLE 1.—*Oil wells completed in United States between 1910 and 1939*

Year	Oil	Gas	Dry
	Percent	*Percent*	*Percent*
1910	73	10	16
1920	72	6	21
1930	55	13	32
1933	66	7	27
1934	69	7	24
1935	70	7	23
1936	72	8	20
1937	72	8	20
1938	70	8	22
1939 (estimated)	68	8	24

Together with improved methods of locating oil deposits have gone improvements in drilling technique. These improvements permit of increasing depth of wells and speed of drilling. There has been a continuous trend toward greater drilling depth, the first test at the 10,000-foot level having been reached in 1931 with first commercial production from it in 1937. The greatest advance in deep drilling has occurred since 1927, and the record-holding depths of producing wells at the end of each year since 1927 are as follows:

Depth of record-holding producing wells

Year:	*Depth, feet*
1927	7, 591
1928	8, 523
1930	8, 550
1931	8, 823
1932	9, 710
1935	9, 836

1936	9,950
1937	11,302
1938	13,266

To attain the present drilling depths has called for many improvements in drilling technique, which together have culminated in the high speed drilling now possible. A record speed is believed to have been 19 days for a 10,000-foot wildcat subsequently abandoned.[1] Among factors influencing this speed are increased rotating speeds from 125 revolutions per minute of some years ago to an extreme of 750 revolutions per minute. In addition, the weight on the bit has been raised to 5–15 tons during rapid rotation, depending upon the formation. The increased drilling efficiency has reduced cost of drilling from an average of $8 per foot, for 3,000–4,000-foot wells, to $3–4 per foot, for 5,000–6,000-foot wells.[2]

Well logging has been improved in recent years and is still a subject of investigation in petroleum production research. A recent development in core logging is the use of pressure cores. Pressure core barrels allow cores to be cut and brought to the surface under pressure, uncontaminated by drilling fluid.[3] Cores obtained in this way "would yield precise information regarding reservoir conditions, such as the quality of oil, gas, and water, and other pertinent subsurface data regarding reservoir pressure and temperature and the permeability of the sand." A number of problems involved in the recovery and analyses of pressure cores remain to be solved. In the meanwhile, two additional methods of well logging are being developed and improved, viz, electrical logging and gamma-ray logging. By electrical logging a complete fluid log of the formations penetrated is possible by means of continuous tests on the mud for oil, gas, and salinity. Gamma-ray logging is based on the radioactive properties of rocks, the intensity of the gamma radiations being used to identify the rock formations.

The advances in oil-field developments have largely come about through research, and the achievements accomplished justify its continuance and expansion. As has been pointed out, whereas "profits resulting from discovery of a new oil field are earned only once . . . profits resulting from improvements in recovery methods . . . apply to all future time . . . ."[4]

Motor Fuels by Cracking

The rapid increase in automobile production, starting about 30 years ago, found the petroleum industry obtaining a country-wide average of only some 10–12 percent of gasoline from its crude oil. To raise this figure, in order to meet the growing demand for motor fuel, became a problem of vital importance to the refiner. As recently as 20 years ago the naphtha stripped from crude oil ("straight run") and recovered from natural gas ("natural") supplied 86 percent of the country's gasoline. At that time the refiner had little or no means of controlling chemical structure and distribution of boiling points of the components

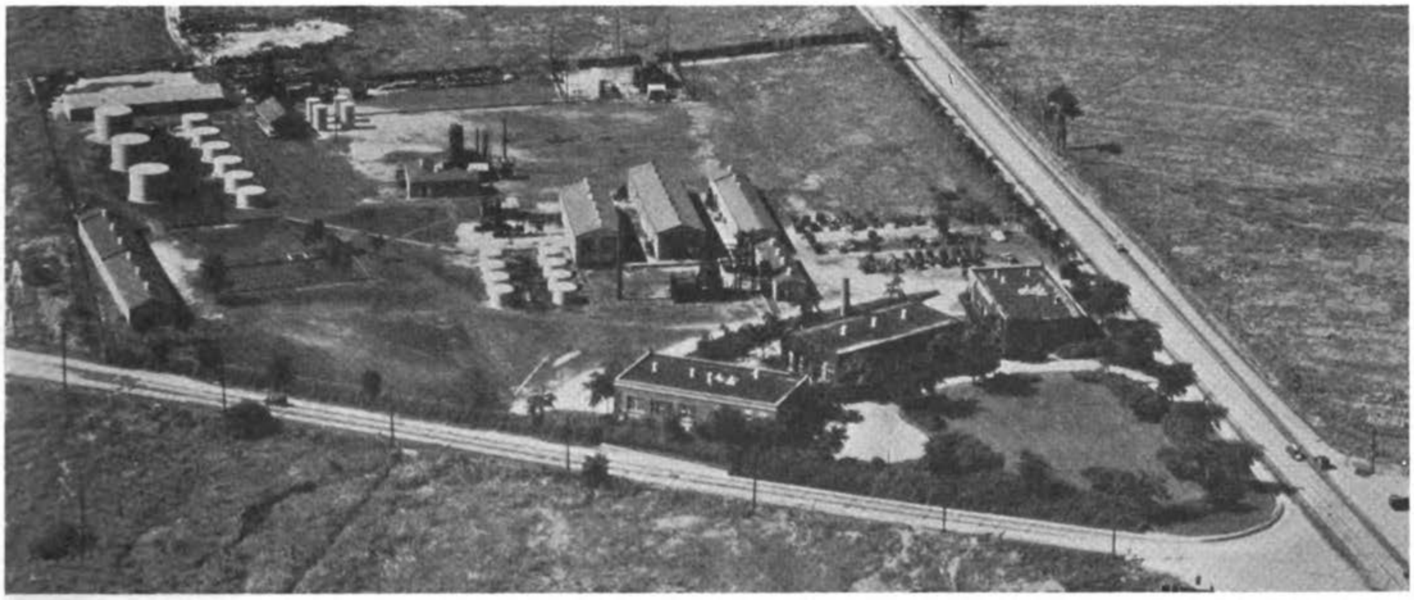

FIGURE 33.—Aerial View of Research and Development Laboratories, Universal Oil Products Company, Riverside, Illinois

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[1] Mills, Brad. Improved practices permit high speed deep drilling. *The Oil Weekly, 94,* No. 8, 66 (July 31, 1939).

[2] Byles, Axtell J. Record oil consumption in 1939 brings reduced profits, record taxes to U. S. producers. *World Petroleum, 11,* No. 1, 21 (January 1940).

[3] Sclater, K. C. A review of oilfield developments and drilling methods. *The Petroleum Engineer, 11,* No. 10, 13 (midyear 1940).

[4] Uren, Lester C. Recent trends in petroleum production research. *The Petroleum Engineer, 11,* No. 10, 17 (midyear 1940).

of gasoline, although later it was found that these properties profoundly influence the performance of the naphtha fractions in the internal combustion engine. However, the discovery that it was possible by thermal treatment to break down the high molecular weight fractions into compounds boiling in the gasoline range pointed the way to a solution of the problem of producing additional motor fuel of improved quality.

In attempting to trace the developments that have taken place during the last two decades it is difficult to consider the petroleum and automotive industries separately, as there is not always a clear distinction between which was cause and which effect. Both industries can perhaps best be thought to have developed along parallel lines, as neither could have reached its present state of development without the impetus provided by the other. At any rate, it was the problems which arose from the development of the industries jointly, more than any other contributing factor, that forced the petroleum industry into research on the chemistry of its raw materials, products, and processes and on the chemical engineering operations involved. Out of the research have come our modern cracking operations which are capable of raising the yield of gasoline on crude oil from an average of some 20 percent to more nearly 65–75 percent. Actually, a lower average figure of about 46 percent is currently being realized country-wide because of the demand for higher boiling fractions, notably in the form of the various types of fuel oils, kerosene, and lubricating oils. The increase in gasoline yield produced by cracking over a number of years is illustrated in figure 35.

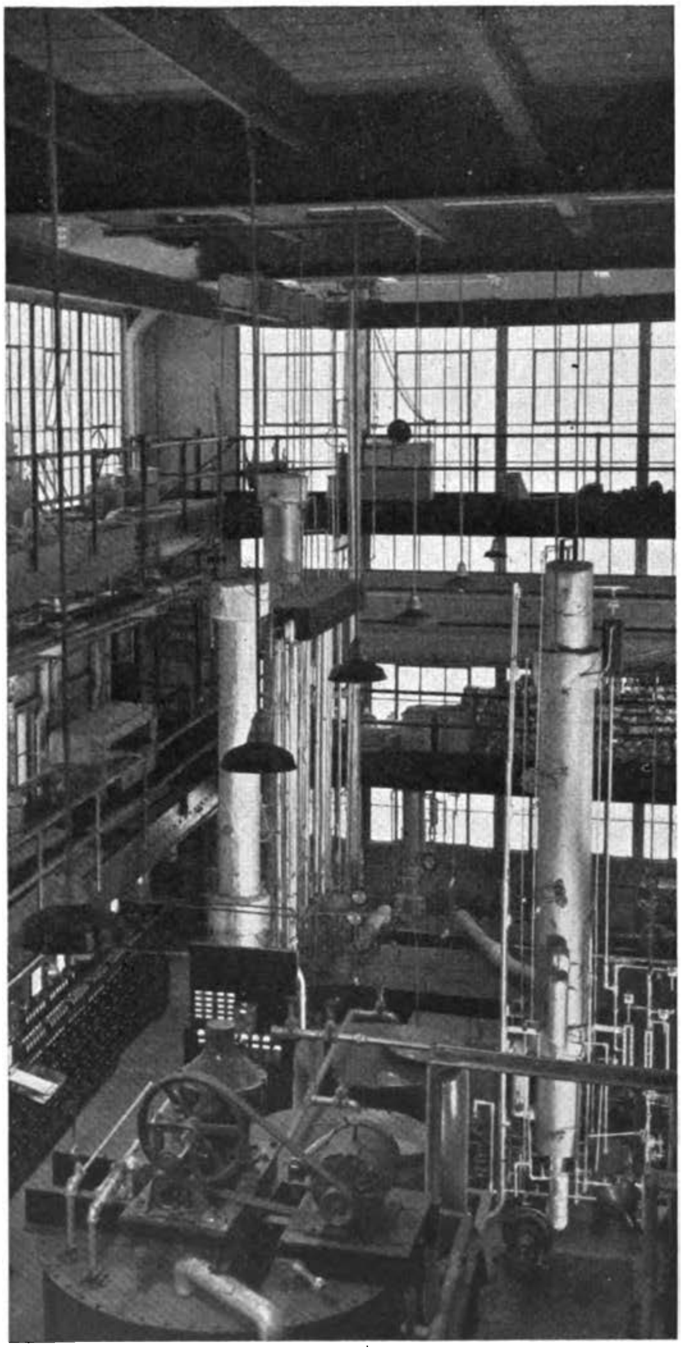

FIGURE 34.—Experimental Oil Cracking Still, Gulf Research and Development Company, Harmarville, Pennsylvania

A comparison of the trend shown in figure 35 with the curve for gasoline production in figure 36 gives an idea of the vast scale on which the cracking operations are being carried out to supply the current demand for motor fuel. Considering that cracking is an operation which is being carried out at temperatures ranging from 850° to 1,200° F. and pressures extending to 1,000 pounds per square inch or more, one may realize the problems involved in equipment design and operation. The early cracking units of 25 years ago were capable of handling only a few hundred barrels of charging

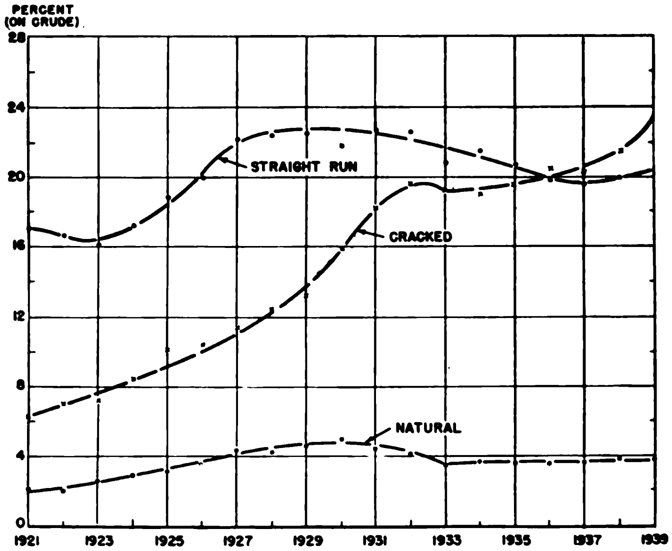

FIGURE 35.—Variations in the Consumption of Straight Run, Cracked, and Natural Gasolines in Terms of Percentages of Crude Oil, 1921–39

stock in a 24-hour day. In contrast to this, the large combination cracking and distillation units now in operation range in capacity to over 35,000 barrels per day, and the operating time between shut-downs for cleaning and repairs has increased from 1 day to 3 months or more. The severity of service conditions for the equipment employed has been a constant stimulus to metallurgists to produce more enduring materials of construction. This is an ever present problem because the petroleum technologist is always ready to employ conditions of temperature and pressure exceeding those possible with the latest developments in special alloys and steels.

The developments in cracking have not been confined to increasing gasoline yield but have also led to marked improvement in quality. By way of illustration, it has become possible to vary the volatility within wide limits by changing the ratio of low- to high-boiling material produced, a matter of considerable importance from the standpoint of adjusting fuel performance to meet seasonal requirements. Within reasonable limits, it is now also possible to alter the chemical composition by controlling the degree of branchiness, the unsaturation, and the aromaticity of the hydrocarbons boiling in the gasoline fractions, which in turn gives products of improved antiknock performance commonly expressed in terms of octane number.

A further advance, improving fuel quality, resulted from the introduction of reforming. The reforming operation is similar to cracking except that it is concerned with raising gasoline quality rather than yield. By the application of heat, the higher boiling naptha fractions of low octane numbers are converted through the processes of isomerization, cyclization, and dehydrogenation, into compounds of higher octane numbers, with some attendant decrease in boiling range and production of gaseous degradation products.

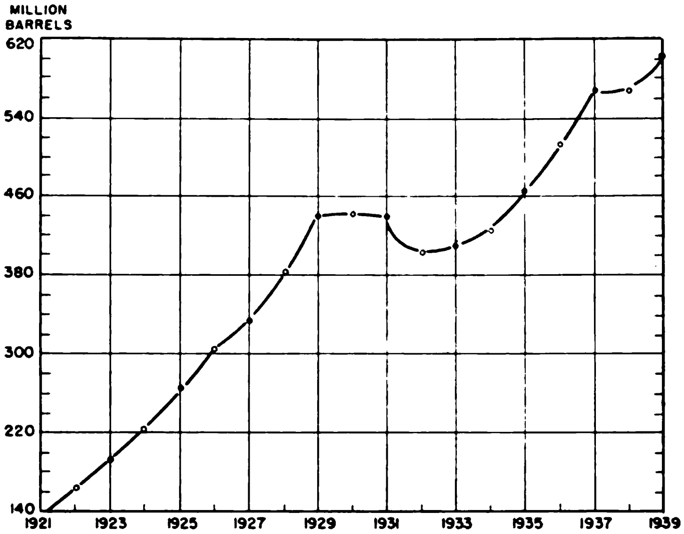

FIGURE 36.—The Production of Domestic Gasoline in the United States, 1921–39

The extensive use of cracking and reforming introduced a new problem to the industry, because of the instability toward oxidation and polymerization of certain of the unsaturated compounds produced. To avoid formation of gum in gasoline, it became necessary to develop new and improved treating methods. And besides treating methods, oxidation inhibitors were developed which when added in minute quantities would greatly improve the stability of gasoline.

Closely related to cracking is the high pressure hydrogenation process for producing gasoline from heavier hydrocarbon fractions. It is capable of wide variations in operating conditions and in results produced. Such destructive hydrogenation can either be directed toward the production of gasoline yields far in excess of those which can be obtained by any cracking process, or toward producing gasoline containing aromatic type products of very high octane number.

Efforts to replace thermal with catalytic cracking processes are already producing promising results. Because of the milder operating conditions and the selective action of the catalysts employed, it is possible in this manner to obtain better over-all yields of desirable products and a gasoline of improved octane number. Although much of the experience gained in thermal cracking can be applied directly here, numerous new problems have been and are still encountered in the development of both catalysts and operating conditions.

Synthetic Fuels

The need for higher gasoline yields and the trend toward gasolines of improved performance with respect to octane rating and volatility, both worked in the direction of more extensive as well as more intensive cracking. Intensive cracking in turn, meant a gradually increasing production of gaseous byproducts, which in addition to the amounts already available as natural gas, became a serious problem to the industry. A variety of methods for converting at least some of these gaseous hydrocarbons back into higher molecular weight compounds boiling in the gasoline range have been developed in recent years as a result of a vast amount of research work. Some of the methods employ straight thermal polymerization under conditions more severe than those normally employed in cracking operations. Other methods depend upon the use of catalysts which selectively polymerize the unsaturated constituents. Still another method known as alkylation depends upon the combining of an olefin with an isoparaffin. The alkylation process can be carried out either by the use of high temperatures and pressures, or at lower temperatures and pressures, by employing sulfuric acid as a catalyst.

In contrast to the more or less random reactions occurring in the cracking of higher hydrocarbons to lower ones, it is possible in the processes concerned with the building up from lower to higher molecular-weight hydrocarbons to direct the reactions toward the formation of a smaller number of reasonably well defined compounds, thus permitting much closer control over both boiling point and chemical structure of the products. As a result, methods of synthesis have become important for the production of fuels of premium quality, particularly from the standpoint of knock-free performance. In fact, although synthetic methods originated in an effort to utilize byproducts, they have within a few years created an entirely new trend in petroleum technology, in that the industry is now concerned with finding adequate supplies of raw materials for their future expansion. This situation has led in particular to an active search for new methods of producing lower olefins by selective cracking and catalytic dehydrogenation of the corresponding paraffins, and for methods of isomerizing available olefins and paraffins into more desirable structures. There is also a great deal of activity in methods of separating these lower hydrocarbons in concentrated form from mixtures containing other hydrocarbons, with varying emphasis on the degree of purity. Because of the superior quality of the synthetic fuels, one can actually visualize that at some future time cracking may be directed primarily toward the production of such low molecular weight olefins as are best suited for the manufacture of fuels of the most desirable hydrocarbon structures—with what now is called gasoline as a byproduct.

Synthetic fuels are the only sources of the high octane number fuels required by the aviation industry. For commercial aviation, fuels approaching 100 octane number in knock rating are highly desirable, since they allow pay loads to be increased by decreasing the fuel consumption for a given power output. For military aviation, fuels of at least 100 octane number are essential to obtain the maneuverability called for in combat.

Lubricants

Among the numerous products of petroleum, lubricants are next in importance to fuels. They cover a wide range of forms—from automotive and industrial oils to greases and extreme pressure lubricants. As in the case of fuels, we find that the progress made in lubricants has largely paralleled developments in the automotive field.

Gradual and continuous progress in distillation and in petroleum treating methods has led to corresponding improvements in the general quality of lubricating oils. Within the last 10 years or so, however, several processes specific to lubricant manufacture have been developed, that have had far reaching consequences on both performance characteristics and manufacturing costs. Modern high grade lubricating oils are consequently decidedly superior to the products supplied only a decade ago with respect to most of the properties by which quality is judged—such as stability to oxidation and rate of deterioration in service, cold-flow characteristics, and loss in viscosity or tendency to thin out at higher temperatures.

Petroleum research has contributed toward the solution of lubricant manufacturing problems along various lines. The low-temperature service characteristics of lubricating oils have been vastly improved by the development of new solvent dewaxing methods and of addition agents which lower the pour or congealing point. Refining by extraction with selective solvents serves to remove undesirable constituents. Removal of these constituents by solvent extraction, on the one hand, produces oils more stable to oxidation and, as a result, more satisfactory for use in high temperature service, and on the other hand brings about a marked reduction in the change in viscosity with temperature, thus broadening the satisfactory operating range for a given lubricant. The latter characteristic can now be still further improved by the use of addition agents which tend to flatten the viscosity-temperature curve. Characteristics such as oiliness and resistance to oxidation can be improved by still other addition agents that are constantly being developed.

Aside from improving quality, the newer refining processes have also made it possible to greatly extend the choice of crudes that can be used for the production of lubricating oils. Indeed, stocks that previously were considered entirely unsuited for work-up into any kind of lubricant, may now serve as the base for the highest grade products. Similar improvements in manufacturing costs have also resulted from this progress in manufacturing methods.

Addition Agents

Early in the history of petroleum in this country it was recognized that certain compounds when added in small amounts considerably modified one or another characteristic of petroleum products. Materials effective in "deblooming," or removing the fluorescence, of light lubricating oils were among the first addition agents, although their use was probably never very extensive Materials intended to stabilize gasolines against becoming off-color have been used for some time and are being quite generally employed. These materials are for the most part commercially available chemical compounds. More recently the petroleum industry has found that compounds heretofore without industrial application, and consequently not available on the market, were particularly effective on certain characteristics. Thus, lead tetraethyl, until some 20 years ago a laboratory curiosity, is now being employed to the extent of over 0.02 percent in more than 2 billion gallons of gasoline per year. The manufacture of lead tetraethyl has, therefore, necessarily grown to become a sizable industry.

It has already been mentioned that among lubricants, addition agents can be used to improve viscosity-temperature characteristics, oiliness, and resistance to oxidation. The pour point—or congealing point of an oil—may also be improved without resort to excessive dewaxing by addition of a suitable pour depressor. In many cases, addition agents remain in the experimental stage, but in other cases they are being produced on a commercial scale. A pour depressor, for instance, has been available to the industry for several years. Without addition agents, the petroleum industry might well find itself unable to meet the demands placed upon fuels and lubricants by modern engines and other mechanical equipment. High engine operating pressures generally mean also high bearing loads and high temperatures. Under these conditions straight petroleum lubricants may fail, however well they are refined. On the other hand, by means of addition agents the lubricants can be made to perform satisfactorily. It is now evident that the demand for addition agents will grow, and that their preparation gradually is creating a new branch in the chemical and in the petroleum industries. The extent of this branch can be seen from the large number of patents issuing in the field. Over 200 patents on lubricating oil additives are known to have been issued in the United States in 1938–39.[5] And, in view of the complicated chemical nature of some of the additives, it is not surprising that many of the patents were issued to chemical concerns rather than to petroleum refining concerns. The future may well be expected to see both a considerable growth in volume in the manufacture of addition agents already in use, and the development of many more agents for specific purposes.

Corollary Effects of Petroleum Research

Having reviewed some of the more important technical results of petroleum research, we now are in a position to consider their bearing on related developments in other industries and, in general, to examine the broader aspects of the subject with emphasis on the social and economic effects that these activities have produced.

New Discoveries and Conservation of Crude Supplies

From time to time, alarming reports have appeared to the effect that our supply of crude oil was faced with a serious decline, or even that it was threatened with exhaustion within a very limited number of years. The best answer to these reports is given by the two curves in figure 32, which show that the industry by and large has been able to add to its reserves through new discoveries and improved production methods. In recent years, increases in reserves have considerably exceeded the volume of crude taken out of the ground over the same periods of time. How long it will be possible to maintain such a favorable balance is obviously impossible to tell. However, the fact that it has been done so far is to the credit of the technologists responsible for the location and efficient recovery of crude. From the standpoint of more complete utilization of a valuable raw material, we have here additional developments supplementing those in the cracking process and related operations, which aim in the same general direction. Without the increased light-end production by cracking, today we should require between twice and three times as much crude oil as at present to meet our country's demand for gasoline.

The fear of a crude oil shortage appeared particularly imminent in the late twenties, when it was predicted that a shortage would begin to be felt within the next decade. As we have already seen, this situation was relieved by discoveries of new oil reservoirs. Had this not been the case, however, alternative sources of oil could have been made available by means of high pressure hydrogenation by extending the research that had led to its development. By means of hydrogenation, crude oil can be converted into gasoline in better than 100 percent yield by volume. As yet the need for a widespread application of hydrogenation has not developed, but here is a process that—whenever the need may arise—would be able to expand greatly the available gasoline supply, admittedly at the expense of heavier fuels.

Effect on Automotive Developments

It has so often been repeated that it seems trite to mention once more that the present-day automobile engine would be totally incapable of operating on the fuels in use in the early twenties. Yet, one can hardly avoid referring back to the early twenties, the time of the discovery of the antiknock value of tetraethyl lead, a discovery which was destined to have such an important bearing on engine design and performance. Nor can one avoid referring to the even more significant gradual progress in cracking, reforming, stabilization, and treating operations that has taken place since that time. These and all other contributions to improvement in fuel quality have been parts of the cooperative efforts that have led to the present-day high compression automobile engine. The general improvement in performance is familiar to every driver from personal

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[5] Van Voorhis, M. G. 200 lubricant additive patents issued in 1938 and 1939. *National Petroleum News, 32*, No. 10, R-66 (March 6, 1940).

experience. Clearly, this improvement is not to be attributed to the progress in fuels alone. And, an indication of the relationship that exists between the parallel lines of development of fuels and of engines may be obtained from figure 37, which shows the increase in compression ratio and improvement in octane number by years.

The high speed automobile engine with its high power output and lightweight construction places rigid requirements on lubrication. As we have already seen, the petroleum industry has contributed to meeting this requirement by the development of oils that retain their fluidity at low temperature, show a minimum change in viscosity on temperature rise, and possess stability toward oxidation in high temperature operation. The magnitude of the problem involved in imparting oxidation stability may be appreciated from the fact that the oil temperature in the crankcase of a light passenger car engine may reach as high as 285° F. under not exceptional driving conditions, and on the piston crown of a heavy-duty bus or truck engine, the oil film is exposed to temperatures of 600°–700° F.

Maintaining adequate bearing lubrication in the face of increasing bearing loads is an ever-present problem. The need for a change from white metal to copper-lead and silver-cadmium alloy bearings, in certain types of high temperature service, has introduced additional complications. The problems have been solved, nevertheless, by the development of lubricants representing further improvements in resistance to deterioration in high temperature service and in freedom from bearing corrosion.

Special problems in chassis lubrication have been solved through cooperative research, and new extreme pressure lubricants have permitted the wide adoption of hypoid gears for power transmission.

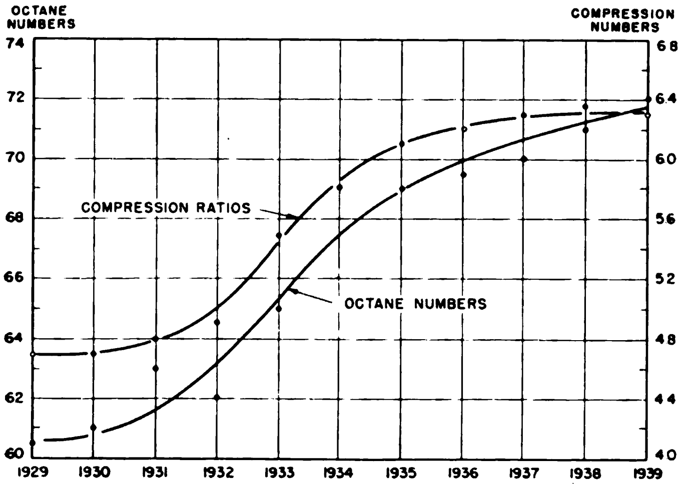

FIGURE 37.—The Trends of Octane Gasoline Ratings and Automobile Engine Compression Ratios, 1929–39

What has been said about the relation of petroleum research to developments in the automobile field holds true, in general, also for aviation—with the exception that the progress in this case has been even more spectacular from the standpoint of both accomplishments and the speed with which the results have been forthcoming.

Only a few years ago the aviation industry had become standardized on a 73-octane-number fuel which—on the addition of 3 cc. of tetraethyl lead per gallon—could be brought up to 87-octane-number. The horsepower output in general did not exceed 40 horsepower, per cylinder. At present, engines of well over 100 horsepower, per cylinder, are running on fuels of up to 100-octane-number, and a great deal of research effort is being expended by the aviation and petroleum industries on extending these limits still further. By going from an aviation gasoline of 87 to one of 100-octane-number, it has been possible to effect a 15- to 30-percent increase in power for take-off and climbing, or a 20-percent reduction in cruising fuel consumption. Where engine design or performance requirements are such that full advantage cannot be taken of the 100-octane-number fuel, fuels of intermediate octane ratings are satisfactory and are finding a wide field of use.

Aviation superfuels, as fuels of 100-octane-number or over are sometimes called, are usually mixtures of a special aviation gasoline base stock, and blending agents, synthetic or natural, to which have been added 3 cc. of tetraethyl lead per gallon. The synthetic blending agents are produced by the previously mentioned polymerization and alkylation processes. The capacity for alkylation, either in operation or under construction, has within about 2 years reached some 12,000 to 15,000 barrels a day. To provide sufficient base stock of suitable high octane number, the natural supplies are at present being augmented by high pressure hydrogenation.

In the 7 years from 1932 to 1939 the gasoline consumed by Government and civil aircraft in the United States increased twofold, from 54 to 108 million gallons annually. During this same period the improvement in aviation lubricants led to a decrease in consumption of from 1 gallon of oil per 37 gallons of gasoline to a ratio of 1 to 42.[6]

Other Industries Affected

It would be practically impossible to enumerate all the industries which in one way or another have benefited directly from the technical accomplishments of the petroleum industry. A plentiful supply of heavy fuel oil has had a profound effect on develop-

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[6] **Norman, H. Stanley. Aviation gasoline assuming increasing importance. *The Oil and Gas Journal*, 38, No. 44, 21 (March 14, 1940).**

ments in ocean transportation. The expansion in the use of oil in marine transportation, particularly of Diesel oil in recent years, can be seen from the following table:

TABLE 2.—*Expansion in world-wide marine transportation between 1914 and 1939*[1]

Item	1914	1935	1939
Tonnage..........tons..	45,403,877	....	68,509,432
Ships..........number..	24,444	....	29,763
Propulsion type:			
Fuel oil..........percent[2]..	2.65	30.65	29.63
Internal-combustion (Diesel)..........do....	.45	17.42	24.36
Total, oil fuel..........do....	3.10	48.07	53.99
Coal..........do....	88.84	50.15	44.67
Sail, etc..........do....	8.06	1.78	1.34

[1] Figures given in Lisle, B. O. European war's influence on world bunkering trade. *World Petroleum, 10,* No. 11, 43 (November 1939), from information given in Lloyd's Register of Shipping. London, Lloyds, 1939–40.
[2] Expressed as percentage of total tonnage.

The marked progress in range-burner and oil-burner performance can in many instances be attributed to improvements in fuel quality. The expansion that has taken place in the field of oil burners can be measured in terms of an increase in the number of domestic oil-burner installations—from 1 million units in 1934 to nearly 2 million units in 1939, now consuming an aggregate of 90 million barrels of fuel per year. Of the millions of homes using automatic heating systems, approximately 57 percent use oil fuel, 28 percent gas, and 15 percent stoker-fired coal.

Developments in distillate fuels, besides their importance in the general field of oil fuels, are also closely related to the progress in Diesel transportation. Both stationary and automotive Diesel engines have confronted the petroleum technologist with complex problems in both lubricants and fuels.

The development of liquefied hydrocarbon gases and of equipment for their use have led to their application in automotive transportation and in special industrial operations—such as the bright annealing of brass—and to a particularly important application in supplying rural districts with a convenient type of fuel.

The expansion in automotive transportation has called for more and more extensive road building. Here the petroleum industry has discharged its obligation by contributing improved grades of asphalt and road oils. It is significant that asphalt consumption for street, highway and airport pavements has increased tenfold in the past 10 years. Bituminous-surfaced roads constituted over 80 percent of all of America's surfaced roads in 1939.[7]

Specialty products have been developed for the process industries. By way of illustration, improved petroleum-base-soluble oils are to an increasing extent replacing fatty oils in the leather and textile industries. Considerable success has also been met with in researches on such products as insecticides and fungicides.

In recent years, the petroleum industry has entered the strictly chemical field to an increasing extent. In general, the developments in any instance are contingent upon the industry's ability to supply a cheap raw material, or to show a low processing cost—or frequently a combination of both—or else the ability to make available an entirely new derivative that does not merely duplicate an existing chemical product. Noteworthy results achieved here are the various alcohols that are being produced in increasing quantities, along with other solvents—such as highly aromatic naphthas—of importance to current developments in paints, lacquers, plastics, etc. The subject of synthetic rubber is being given increasing attention. Important developments are now in progress in this country, and it would seem that the petroleum industry should be in a particularly good position to supply the raw materials required should it ever become desirable to compete with the imported natural product on a volume basis. According to recent announcements, the production of synthetic rubber from petroleum derivatives will soon be carried out commercially in this country.

General Effects on the Public Economy

The public at large has benefited in many ways from the achievements of petroleum research reviewed in the previous sections. This fact is illustrated by the increased efficiency in refinery processing which contributes to the conservation of available crude supplies, by the improved car performance resulting from better fuels, and by the decreased cost of repair and upkeep that can be attributed to more stable lubricants and cleaner burning fuels.

Our entire mode of living has been profoundly influenced by the advances in automotive transportation. We find petroleum research contributing directly to the increased passenger car registration, low cost of travel by bus, low cost transportation of merchandise by motortruck, and decreased cost of air travel. The low-cost, high-quality roads made possible by improvements in asphalt and road oils have helped to open the country to the motoring public. Even the increase in tire mileage and equally amazing lowering in tire cost can to no small extent be attributed, at least indirectly, to hydrocarbon solvents and other petroleum derivatives. At some future date the petroleum industry may perhaps also contribute the rubber that goes into the manufacture of automobile tires.

The advantages that have accrued to the public have by no means been restricted to the automotive field. Far from being engaged chiefly in supplying fuels for industries in competition with older means of trans-

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[7] Asphalt consumption for paving increases tenfold in decade. *National Petroleum News, 32,* No. 12, R-91 (March 20, 1940)

portation, the petroleum industry is now cooperating in the development of fuels and lubricants for Diesel-driven rail equipment, with which the railroad industry hopes to regain lost territory.

Leaving the field of transportation, we find that the contributions to the domestic fuel situation have placed the convenience and comfort of the oil burner within the reach of the average citizen. Like the rest of us, the farmer is becoming increasingly dependent upon petroleum products. Perhaps he has been benefited as much by the industry's contribution to his fight against the insect pests in their various forms as by its contribution to his transportation facilities and the mechanization of his equipment.

Although the average automobile driver does not think of this in terms of petroleum research, he knows full well that his bill for fuel and lubricants has undergone a most noticeable reduction in recent years. This is illustrated in figure 38 which shows the average retail price of regular gasoline on a country-wide basis from 1921 to 1939. Even the rapid growth of taxation, as expressed by the difference between the upper and lower curves, has not succeeded in camouflaging the results produced in terms of decreasing cost. As a result of the decreasing gasoline price it has been possible for Federal and State authorities to collect increasing tax revenues without increasing the cost of gasoline to the consumer. For example, comparing the years 1930 and 1937, it will be seen that the service station price of gasoline in both years was approximately the same, viz, 19.8 to 19.9 cents per gallon. However, the increases in the tax rate and in gasoline consumption would permit tax revenues to increase from some $70,000,000 in 1930 to over $1,000,000,000 in 1937.

Considering that the refinery billing price for gasoline has reached the low level of 5 cents per gallon—or even less[8]—it is unlikely that there will be any further marked decrease in cost on a gallon basis. However, further improvements in gasoline quality—when taken in connection with possible improvements in engine design—may well lead to an additional decrease in fuel cost on a mileage basis.

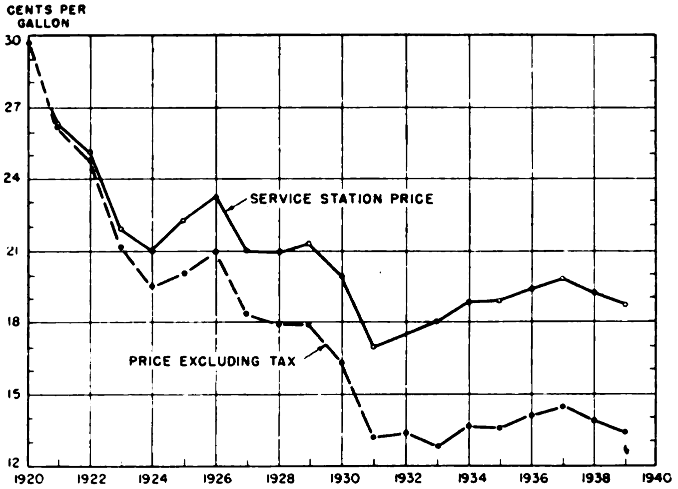

FIGURE 38.—Variations in the Price of Gasoline in the United States, 1920–39 (based on prices in 50 cities)

Effect on Employment

To determine the full effect of petroleum research on employment, we should have to make a careful analysis of those expansions—as well as any contractions—in industrial activities that might be traced to definite technical contributions to progress in the petroleum field. Such a survey would have to take into consideration all kinds of automotive transportation—including the manufacture of automobiles, aircraft, and motor-driven farm equipment, together with all contributory industries—railroad transportation, shipping, coal mining, distribution systems responsible for the delivery of domestic heating oil and bottled gas in rural areas, etc. As this is clearly beyond the scope of the present article, we shall have to limit our discussion to employment in the petroleum industry itself.

The many technical improvements cited in the earlier sections have quite logically resulted in an increased efficiency with respect to the manpower required in the petroleum industry's production and manufacturing operations. This holds true particularly for the processes involved in refining of petroleum products. As a result of this, the number of wage earners employed in the United States in petroleum refining per million barrels of crude oil run to stills has decreased from 234 in 1899 to 70 in 1937. However, the expanded operations have more than compensated for this trend, so that the net result has been a greatly increased rate of employment, as shown by the following figures:[9]

Estimated United States refinery wage earners

Year:	*Number*
1900	13, 550
1910	14, 700
1920	61, 300
1930	76, 200
1939	83, 200

As might be expected, there has been an enormous increase in the number of technical men employed. A recent survey gives the following figures for total personnel engaged in petroleum research:[10]

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[8] Gulf coast prices.

[9] Estimated from figures given in U. S. Department of Commerce, Bureau of the Census. Census of Manufacturers. Washington, U. S. Government Printing Office.

[10] Perazich, G., and Field, P. M. Industrial research and changing technology. Philadelphia, Pa., Work Projects Administration, National Research Project, *Report No. M-4*, 1940, pp. 41-42.

Research personnel

Year:	Number
1920	145
1921	167
1927	788
1931	2, 957
1933	2, 724
1938	5, 033

Because of the difficulty of obtaining complete information of this nature, it may be assumed that the figures are on the conservative side. It may further be assumed that somewhat less than half of these numbers represent technically trained personnel. This rapid growth has placed the petroleum industry second only to the chemical industry as an employer of research workers in relation to the number of wage earners.

A large section of the petroleum industry is engaged in selling products. As indicated above, the products may vary from crude oil, automotive fuels and lubricants, industrial and process oils, to specialties such as pharmaceuticals and cosmetics. Every addition to the volume or variety of products means an increase in the personnel required to market and sell the products.

Research Methods and Policies

In view of the magnitude of the field, it may be useful to attempt an analysis of the way in which research is being carried out by the petroleum industry and of the general policies that govern the work.

How and Where the Research Is Done

In the early days of petroleum research the work was sponsored almost entirely by the major oil companies. This situation has now changed completely in that research may be said to be carried out by the industry as a whole. In a field where progress is so rapid, it becomes necessary for the management in any one organization to depend more and more on highly skilled and technically trained personnel to follow the current developments within the whole industry in order to keep its own operations abreast of competition. Not the least important duty is to scrutinize with care new developments originating either within the organization or on the outside so as to avoid costly mistakes in their evaluation.

Common interests frequently make for cooperation between companies on joint development projects.

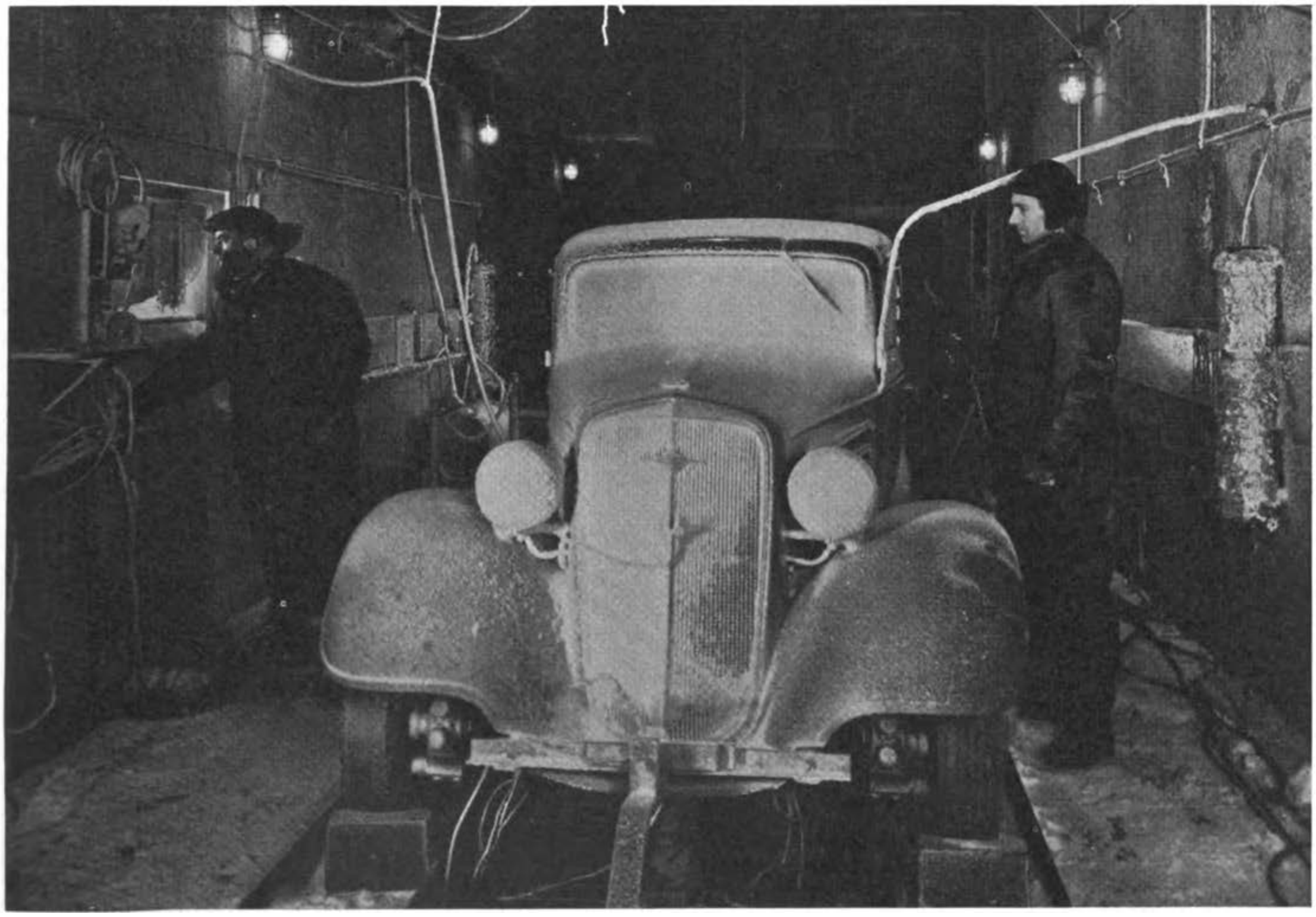

FIGURE 39.—Subzero Temperatures for Study of Oil, Fuel, and Lubricant Performances, Standard Oil Development Company, Elizabeth, New Jersey

Such cooperative programs may involve equipment manufacturers and service companies whose business is closely related to developments within the petroleum industry. The joining of efforts in joint projects may be stimulated by various causes; it is resorted to particularly in those cases where otherwise complications of a legal nature are apt to seriously delay an important technical development with consequent loss to the industry as a whole.

Research programs of broad interest to the industry—or to an important group within the industry—particularly when they are on problems of a fundamental character, are frequently also handled on a cooperative basis. Illustrations of this are the project on the composition and structure of petroleum carried out at the National Bureau of Standards under the sponsorship of the American Petroleum Institute; the Hydrocarbon Research Project, sponsored jointly by 25 oil companies and the General Motors Research Laboratories, at Ohio State University; and the studies on composition and processing of Pennsylvania crude oil, being conducted at Pennsylvania State College for the Pennsylvania Grade Crude Oil Association.

Relation to the Universities

The increased employment of technical personnel by the petroleum industry has clearly had an effect on our teaching institutions. This is particularly noticeable in the case of the chemical engineering education in some schools, where the curricula place a great deal of emphasis on the unit operations employed in petroleum refining. The growing trend toward instruction in petroleum technology in engineering curricula has been stimulated not only by the demand for graduates possessing specialized training along such lines, but also by the return to the teaching profession of men trained in the petroleum industry, particularly in its research and development organizations. Moreover, many professors of chemical engineering are actively engaged as consultants by the petroleum industry and thereby acquire an intimate knowledge of its processes and operating methods.

As a result of the study of petroleum-refining operations by institutions of learning, there has been a marked contribution from leading universities to the progress in petroleum along chemical engineering lines. Along strictly chemical lines, however, contributions from universities have perhaps not been so pronounced. In fact, most of the new organic chemistry dealing with aliphatic hydrocarbons and applicable to the processing of petroleum, has originated within the petroleum industry itself. With some notable exceptions, our universities do not stress sufficiently strongly teaching and research in this field. Considering the technical and economic importance of the petroleum industry, it is to be hoped that the potentialities of its basic raw material may receive more attention among teachers of organic chemistry. Physical chemistry, through its newer trends, already promises to contribute to a considerable degree toward the solution of the petroleum industry's problems.

A System of Free Competition

It is to be expected that a field, in which technical progress is so rapid, should leave ample room for free competition. In this respect, the petroleum industry has retained its pioneering aspect even at this late date. In spite of the large integrated technical organizations of the major oil companies—and in spite of the cooperative research efforts previously discussed—there are no obstacles in the way of individual initiative. In fact, many of the important developments in petroleum have been—and continue to be—contributed by individuals not directly employed by the industry.

It is evident that research can defeat any attempt toward monopolizing a broad field in the petroleum industry, as it can find other ways and means of accomplishing the same or even better results than currently obtained. The rate at which new processes are being developed, with the attendant threat of rapid obsolescence, encourages quick utilization of new developments both by the inventor himself and through licensing to competitors. There invariably seems to be more than one solution to a given problem, as illustrated by the numerous cracking processes that have been developed by competing oil companies and individuals. The same situation exists in the more recent accomplishments, such as solvent extraction, where a large number of different processes are in commercial operation, and in the many polymerization processes for the production of premium fuels. Even catalytic cracking, which was first announced only 2 years ago, already has produced no less than three competing processes.

Characteristic of petroleum research also are its generous contributions of subjects for inclusion in programs of technical society conventions and meetings, and of papers for publication in technical journals. The publicity given, in this way, to the results obtained by an individual or by a group of individuals encourages efforts by others, where a more secretive policy would tend to lessen competition.

Perhaps the general spirit of community of interest in the field of petroleum research can best be expressed by a quotation from the acceptance speech recently given by a petroleum executive on the occasion of an award for achievement in this field of endeavor: ". . . we are indebted at every stage of the development to contributions from other organizations—often our competitors." [11]

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[11] Award for chemical engineering achievement. Achievement via group effort. Howard, F. A. Acceptance. *Chemical and Metallurgical Engineering, 46,* 751 (December 1939).

SECTION III

3. RESEARCH IN THE IRON AND STEEL INDUSTRY

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ABSTRACT

Research by the iron and steel industry of the United States (and of other countries as well) is carried out for the purpose of improving methods of manufacture and quality of products, reducing cost, developing new products, new uses and new markets for old products. In addition the technical staffs of the industry carry out considerable research jointly with the users of steel and act as consultants to steel consumers who have no research laboratory of their own. During the last 10 years the average expenditure for research has varied between $8 million and $10 million per year, more than 10 times the amount it was 15 years ago. Although the industry as a whole reduces its expenditures for research in depression years, the reduction is never proportional to reduced production. As a result the number of reports of research published increases greatly in depression years.

Large steel companies have a central research laboratory in which research of value to the company as a whole is carried out, which acts as a training school for plant metallurgists, and which cooperates on important problems with the technical men in the various mills. Research personnel is largely college trained and includes metallurgists, chemists, engineers of various kinds, and many others, about one-quarter or one-third of whom hold doctors' degrees.

Although considerable cooperative research is done by the iron and steel industry of the United States, this phase of research has not been developed to such an extent as in Germany and England. Research for the benefit of the entire industry, for which the industry as a whole supplies the funds and institutes and universities supply the facilities, is the weakest phase of ferrous metallurgical research in the United States.

The economic consequences of research by the iron and steel industry in all the principal steel-making countries have been far reaching. Pig iron, carbon steel, and alloy steels are being produced to quality standards unheard of 20 years ago; moreover, this improvement in quality has been attained with no increase, and in some instances with a large decrease in cost. Increasing the quality of carbon steel, developing a new series of cheap, high-strength, low-alloy steels, and producing stainless steels in large tonnages have revolutionized automotive and aircraft design and have produced changes in transportation, oil refining, and other industries with remarkable savings in cost and increase in efficiency.

Research, as carried out in the iron and steel industry, may be divided into two general classes; viz, process and materials research, and fundamental research. Process and materials research is naturally the most important and widely practiced and has a fourfold purpose: (1) Improving quality, (2) improving methods of manufacture and reducing cost, (3) developing new products, and (4) developing new uses and new markets for old products.

Fundamental research in the iron and steel industry seeks to discover the underlying causes of metallurgical phenomena; its primary aim is to add to metallurgical knowledge, and it is usually carried out in the universities and technical schools, in cooperative research institutes, or in Government laboratories; only a relatively small part has been done in steel-works laboratories. On the other hand, most of the process and materials research is carried out by the steel industry, although the staffs of some universities and research institutes direct more effort to ferrous materials and processes than to the fundamentals of metallurgy.

The Role of the American Iron and Steel Industry in the Development of Research

Most of the great developments in the iron and steel industry occurred in the last half of the nineteenth century. As shown in table 1, nearly 40 percent of these originated in England where the industrial revolution had been under way for nearly a century, far longer than in any other part of the world. Of the other countries which are now leaders in iron and steel production, the United States, Germany, and France each contributed about 20 percent to the advance of the industry, although, as table 1 indicates, the United States was far behind France and Germany (at the time more advanced in industrial policy) in contributions to a fundamental knowledge of metallurgy.

TABLE 1.—*Advance in the iron and steel industry, 1850 to 1900* [1]

Country	Number of contributions to—		Total
	Improvement in processes and products	Fundamental metallurgical knowledge	
England	23	25	48
United States	20	3	23
Germany	14	10	24
France	9	14	23
Sweden	1	6	7
Total	67	58	125

[1] Data for table 1 based on Goodale, S. L. Chronology of iron and steel. Pittsburgh, Pa., Pittsburgh Iron and Steel Foundries Co., 1st ed., 1920.

Contributions of England in the Nineteenth Century

The industrial world owes a large debt to the inventive and scientific genius of some 10 or 15 Englishmen who in the last half of the nineteenth century revolutionized the steel industry and in addition founded the science of physical metallurgy. The Bessemer process of refining pig iron by blowing air through the molten metal was invented in 1856 by Henry Bessemer and was made a commercial success by the metallurgical genius of Robert Mushet.[1] This process made it possible for the first time to produce steel cheaply and in large tonnages and was the most important single factor in the development of our present-day industrial economy, which is built upon cheap steel.

Other outstanding developments of processes in England during this period were Siemens' discovery of the regenerative principle which resulted in the open-hearth process, the hot blast stove for the blast furnace, the reversing mill, the continuous rod mill, and—perhaps most important—the discovery by Thomas and Gilchrist that lime removes phosphorus from molten high-carbon iron, thus making it possible to use the enormous world deposits of iron ore containing a relatively large amount of this element.

England's contributions to the development of ferrous materials were numerous. The most outstanding were Mushet's air-hardening tool steel and Hadfield's extensive work on alloys of iron with manganese, chromium, and other elements which played an important part in the development of knowledge that has led to present-day alloy steels.

During this period, several Englishmen were engaged in fundamental research on iron and steel. Sorby was the first to use the microscope for the study of the structure of metals; this was the beginning of a science of physical metallurgy. Barrett discovered recalescence and its relation to the hardening of steel, and Arnold did pioneering work in correlating the chemical composition and the properties of ferrous materials. Valuable textbooks were written by Percy, on the metallurgy of iron and steel (1864), and by Bell, on the chemistry of the blast furnace (1872); these had marked influence on the iron and steel industry everywhere.

Contributions of the United States in the Nineteenth Century

The iron and steel industry of the United States, using the developments outlined above, grew from adolescence to manhood in the last three decades of the nineteenth century. During this period, pig-iron production increased from 2 to 14 million tons and steel production from less than 100,000 tons to 10.5 million tons. The most important cause of this rapid expansion was the building of the railroads; miles of track increased from 50,000 in 1870, most of which was laid with iron rails, to 260,000 in 1900, nearly all of which was laid with steel rails. With the introduction of the Bessemer process other uses of steel expanded rapidly, especially for bridges and buildings, and for agricultural purposes. Four billion dollars was spent in fencing the farms of the United States during this 30-year period; at least 75 percent of this sum was represented by purchases of iron and steel products.

Between 1870 and 1900 the steel industry of the United States was so busy building up the country that there was little time, and less incentive, for research even in the broadest sense of the word. Most development work had as its primary object the reduction of cost; this was so successful that in the last decade of the century the steel industry of the United States was underselling the British in world markets, with the result that the British Iron and Steel Institute sent a delegation to the United States to see how it was done.

Among the developments which were important in lowering costs were more efficient blowing engines for blast furances, many improvements in rolling mills, most of which came from the fertile brain of John Fritz, and—most important—the development of efficient machines for large-scale production of barbed wire, fences, nails, and springs. Although the United States did not pioneer the use of steel for building and bridge construction, the skyscraper and the long suspension bridge are American developments.

Only one noteworthy development in steels originated in the United States during the last half of the nine-

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[1] William Kelly in the United States probably anticipated Bessemer's invention by nearly 10 years but was never able to make the process work satisfactorily. The credit for the invention is, therefore, usually given to Bessemer, although it is claimed by some that without the help of Mushet he would have made no more headway than Kelly.

teenth century, but this probably had as important ramifications in industry generally as any that ferrous metallurgy has known. This was the discovery by Taylor and White, in 1894 to 1898, of high-speed steel and of the heat treatment necessary to give the steel its unique property of red hardness, i. e., the ability to keep its cutting edge when operating at such high speeds that the tool gets red hot. The steel itself was an outgrowth of the original Mushet air-hardening process, but the heat treatment was unique. High-speed steel completely revolutionized the machine-tool industry and made tungsten, its principal alloying element, a strategic material of first importance.

Little research on metallurgical fundamentals was carried out in the United States before 1900. Albert Sauveur was the first in this country to study the structure of steel with the microscope (1891–93), and Henry Marion Howe, at Columbia University, won world-wide fame as an investigator of the constitution of iron-carbon and other alloys. Howe's book on metallurgy, published in 1890, was for many years a classic in this field.

Contributions of Other Countries in the Nineteenth Century

As pioneers in metallurgical research both Germany and France rank as high as the United States. In one sense they rank higher, as Germany was producing only 10 to 17 million tons of steel and pig iron, and France only 5 to 7 million tons, as compared with an annual total of 18 to 25 million tons for the United States.

Research in France during the last half of the nineteenth century resulted in a number of important developments in processes. French engineers discovered how to coke bituminous coal in closed retorts, so that the valuable byproducts could be recovered, and perfected the electric arc furnace as a means of melting steel and nonferrous alloys. They were also the first to build armored naval vessels and to use steel in building construction. As the result of research on materials, French scientists were the first to produce ferromanganese on a commercial scale and were primarily responsible for the discovery of iron-nickel alloys having unique expansion, magnetic, and electric characteristics, which have been an important factor in the development of an efficient communications system. In research in fundamentals, the French rank next to the British. Osmond discovered the allotropy of iron, and Le Chatelier perfected the pyrometer and the metallurgical microscope; these were of prime importance in the development of a science of physical metallurgy.

Of the 24 important contributions made by Germans to the improvement of processes and products, and to furthering metallurgical knowledge, the following are outstanding: The universal mill, the hydraulic forging press, producing cement from slag, and acetylene which is now used widely in welding. Martens and Wedding made important contributions to physical metallurgy. Equally outstanding is the work of Wöhler who, between 1850 and 1870, investigated the failure of metals under repeated stress and established the existence of fatigue phenomena.

Of the countries not mentioned only Sweden was an early contributor of anything of importance to the development of the iron and steel industry. The work of Eggertz on chemical analysis of iron and steel is noteworthy, as is Brinell's development of a simple test for determining hardness.

World Research in the Iron and Steel Industry, 1900 to 1930

A comparison of research in ferrous metallurgy over the first 3 decades of the twentieth century for the four principal steel-making countries of the world is given in table 2. The amount of research in any one country naturally varies with the size of the iron and steel industry; thus, more has been done, especially since the First World War, in the United States than in any other country. To consider only the volume of actual research would, therefore, not give a true picture of the research-mindedness of the industry or of the country; hence recourse was had to calculation of a research factor. This factor was obtained by dividing the number of reports which contributed to the advance of the industry or to fundamental knowledge in ferrous metallurgy, as published in the technical press, by the total production of steel ingots plus pig iron, in millions of metric tons.[3]

There are, of course, several objections to a comparison of this sort. In the first place, the results of many research projects, especially those which produce an improvement of processes, are never published. In the second place, it is practically impossible to separate reports of metallurgical research done by the industry itself from reports of research done by the universities and Government laboratories. This is especially true for Germany where the Kaiser Wilhelm Institut für Eisenforschung and the Technische Hochschule at Aachen (among others) do a large amount of work, especially of the more fundamental kind, for the steel industry. In the third place—and this is the most important variable—the accuracy of such a comparison

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[3] Data on steel-ingot and pig-iron production are from The mineral industry. New York, Scientific Publishing Co., 1893–1935; Minerals yearbook. Yearbook of the Bureau of Mines. Washington, U. S. Government Printing Office; data on published papers from bibliographies of Alloys of iron research. (Monograph series, 6,000 papers). New York, McGraw-Hill Book Co., 1932–1939; supplemented by a review of the abstract section of the *Journal of the Iron and Steel Institute* (British), (1900–1930).

TABLE 2.—*Amount of research by the principal iron- and steel-making countries, 1900 to 1930*

TOTAL RESEARCH

Year	United States			Germany and Austria			Great Britain			France and Belgium		
	Production, million metric tons	Number of papers	Research factor	Production, million metric tons	Number of papers	Research factor	Production, million metric tons	Number of papers	Research factor	Production, million metric tons	Number of papers	Research factor
1900	24.2	79	3.26	17.7	81	4 57	14.1	69	4.87	6.1	34	5.57
1905	43.7	186	4.25	23.6	184	7.79	15.7	123	7.83	7.6	68	8.90
1910	53.1	121	2.28	32.7	149	4.57	16.9	101	5.94	10.9	44	4.00
1919	66.7	201	3.00	13.9	54	3.86	15.5	86	5.55	5.2	41	7.89
1923	85.3	169	1.98	17.1	97	5.70	15.9	77	4.81	14.8	47	3.18
1928	89.7	291	3.23	39.0	280	7.17	15.1	134	8.93	27.2	41	2.98
Average			3.00			5.61			6.32			5.42
FUNDAMENTAL RESEARCH												
1900	24.2	16	0.64	17.7	20	1.13	14.1	19	1.32	6.1	14	2.26
1905	43.7	38	.87	23.6	62	2.64	15.7	28	1.75	7.6	17	2.25
1910	53.1	27	.51	32.7	47	1.43	16.9	25	1.46	10.9	21	1.94
1919	66.7	44	.66	13.9	11	.80	15.5	24	1.53	5.2	11	2.08
1923	85.3	47	.55	17.1	27	1.50	15.9	16	1.01	14.8	7	.46
1928	89.7	59	.66	39.0	56	1.49	15.1	23	1.52	27.2	14	.51
Average			.65			1.45			1.43			1.58

as is given in table 2 depends to a large degree on the judgment of the individual making the comparison, especially in what constitutes significant research.

Each of the factors in the top half of table 2 is the sum of the factors obtained for four main divisions of metallurgical progress, namely: (1) Important developments in the manufacture of steel and cast iron, (2) important developments in the treatment of steel, including mechanical working, heat treatment, welding, coatings, and other operations connected with these, (3) research in the constitution and structure of carbon and alloy steels and plain and alloy cast irons, and (4) research in the properties of ferrous materials.

Each of the factors in the lower half of table 2 was obtained by taking into account only the published papers dealing with constitution and structure, the physical chemistry of steel making, theoretical treatments of mechanical deformation, theory of heat treatment, and other subjects which were considered to have advanced the science of physical metallurgy.

Comparison of Research in the World, 1900 to 1930

If it is assumed that the data given in table 2 represent with reasonable accuracy the status of world research in the iron and steel industry from 1900 to 1930, several interesting conclusions can be drawn. First, and most important: It is clear, considering the size of the industry in the United States, that only about half as much total research was done in this country between 1900 and 1930 as in each of the other three countries. The proportion of fundamental research was even less. Another interesting fact is that the amount of fundamental research (in relation to iron and steel production) in the United States and in Great Britain remained fairly constant for the 30 years under consideration.

In Germany and France the amount in proportion to production varied more erratically. Fundamental research in Germany fell off immediately after the First World War but bounced up remarkably by 1923 when the inflation was at its height, despite the fact that production did not increase greatly. France contributed a great deal proportionately to metallurgical knowledge in the first decade of the century. In the third decade the research factors are much lower; the amount of research did not increase as production increased. Another interesting point is that, although there is a tendency for the amount of research, especially of the fundamental sort, to decrease in depression years, the research factor is also lower when there is a sudden boom in the industry. Apparently this is due to lack of time for the work rather than to lack of money. Such a condition is shown for the United States, Germany, and France in 1910 (table 2).

Despite an annual production of steel ingots plus pig iron of less than 1 million tons, Swedish metallurgists publish between 10 and 20 papers a year which are without question definite and valuable contributions to the iron and steel industry, especially to fundamental knowledge. No research factors have been calculated for Sweden as the number of papers and the production of ferrous materials are so small that such a factor would mean very little. Considering the size of the country, however, the research work of its metallurgists is of considerable importance.

The contributions of Italian research workers to the advance of the iron and steel industry have been few, with the exception of the work of Stassano on the electric furnace and of Giolitti on heat treatment. Reports of importance varied between 5 and 10 annually in 1900 to 1930. Italy's combined production of pig iron and steel ingots ranged from 500,000 to 2,000,000 tons annually in the same period.

Little work of interest was done by Japanese metallurgists until after the First World War, when the research of Honda, Murakami, Sato, and a few others, most of whom were connected with the Tohoku Imperial University, attracted attention. Most of the work of the Japanese metallurgists has been on the constitution of carbon and alloy steels and on the development of magnetic materials; nearly all their reports have been printed in English or German.

Russia contributed little to the advance of the iron and steel industry prior to the revolution and practically nothing between 1917 and 1925. Of the relatively large number of reports published in Russian since 1925 fewer than 20 or 30 contain anything of real value.

Outstanding Developments in the World Iron and Steel Industry, 1900 to 1930

It is not within the scope of this paper to outline all the important developments in the iron and steel industry of the world for the first 30 years of this century. They have been so numerous and so many printed pages would be needed even to catalog them that it is necessary to limit the discussion in this section to a few outstanding examples.

It is only necessary to note that the output of the blast furnace approximately tripled between 1900 and 1930 to realize that a large amount of important research has been done on this phase of the iron and steel industry. To effect this progress, extensive studies have been made on the beneficiation of ores, the improvement of the quality of coke, on slag reactions and their influence upon the production and quality of the iron, and especially on the general design of the furnace itself. Improvements in these directions have been achieved in all principal iron-making countries but have been particularly pronounced in the United States.

The most important research work in steel making, which has been devoted chiefly to the physical chemistry of slag-metal reactions in the basic open-hearth process, was pioneered in this country by C. H. Herty, Jr., and his associates under the auspices of the Metallurgical Advisory Board of the United States Bureau of Mines and Carnegie Institute of Technology, and in Germany by H. Schenck and his associates, working at the Krupp laboratories. This work got actively under way about 1925 and is still going on at the Krupp works and at a number of places in the United States. It has had important ramifications in improving the quality of carbon steel and has been accompanied by valuable work on gases and nonmetallic inclusions in molten and in solid steel. The most comprehensive and valuable work along this line in England has been that of a committee of the British Iron and Steel Institute which started in 1925 to study the heterogeneity of steel ingots; this work is also still under way.

Alloy steels, the development of which started late in the nineteenth century, were used rarely, except for armor and ordnance, until after the First World War, when the rapid development of the automotive, aircraft, and petroleum-refining industries began to require relatively large tonnages. This is shown clearly by the increase in production from 570,000 tons in 1910 to about 4 million tons in 1930.

Two developments in alloy steels are outstanding: The "stainless" materials and the low-alloy structural grades. There are, as is well known, two classes of stainless steels: The hard cutlery steels, containing 0.30 to 0.40 percent of carbon and 11 to 14 percent of chromium, and the soft austenitic steels, widely used for structural and ornamental purposes, containing low carbon and about 18 percent of chromium and 8 of nickel. Credit for the discovery of cutlery steel belongs to Brearley, an Englishman, whose research resulted in the patenting of this alloy in 1913. The so-called 18-8 steel is a development by Strauss and Maurer, working at the Krupp laboratories in 1909 to 1912.[3]

The large class of low-alloy steels now being used widely as structural materials, especially for railroad rolling stock and to a lesser extent for ships, bridges, and buildings, is an outgrowth of experience with a few

FIGURE 40.—Research on Creep of Steel, Crane Company, Chicago, Illinois

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[3] Thum, E. E. The book of stainless steels. Cleveland, American Society for Metals, 1935, pp. 1-8. In ch. 1 the development of these steels is discussed in detail.

of these materials in the United States, England, and Germany, as early as 1910 to 1915, for highly stressed members of bridges and ships. Some 30 of these steels are known at present, most of which were placed on the market in the last 10 years. The economic significance of these steels is discussed in a later section.

There are two important advances in the steel industry for which American research workers are almost solely responsible. One, controlled grain size, is primarily a metallurgical development. It was first called to the attention of metallurgists by McQuaid and Ehn in 1922 and has received much attention in the past 15 years, with the result that grain size is now a part of some steel specifications. Grain size affects machinability, response to heat treatment, and the hardness of heat-treated steels. It is controlled by appropriate regulation of the melting process. The continuous-strip mill, developed by the American Rolling Mill Company in 1925 and 1926, has reduced the cost and improved the quality of thin flat-rolled steel so much that automotive design has undergone radical changes in the past 10 or 12 years. This, too, is discussed later.

Present Status of Research in the Iron and Steel Industry

Although metallurgists have been employed by American steel companies and although sporadic research has been undertaken by a few of the companies for nearly 50 years, metallurgical research as an organized activity of the industry became widespread only about 15 or 20 years ago. Credit for the establishment of the first research laboratory, designated as such, at one of the larger plants is usually given to the American Rolling Mill Company, which began research on ingot iron as early as 1903; 6 years later 12 research workers were employed there.

Most of the smaller steel mills making a specialty of the manufacture of alloy and tool steels employed one or more research metallurgists between 1900 and 1920. In many cases, however, these metallurgists were engaged in "trouble shooting" rather than in research work. Between 1920 and 1930 the value of research as a separate centralized activity became apparent to some of the larger companies; the Bethlehem Steel Company began research on a large scale in 1926, and Jones and Laughlin followed a year or two later. The central research laboratory of the United States Steel Corporation was established in 1928, although the subsidiary companies, especially Illinois Steel Company and Carnegie Steel Company, had employed metallurgists and other technical men for research as early as 1908.[4]

Purpose of Research in the American Iron and Steel Industry

As noted on the first page of this paper, most research in the iron and steel industry is on processes and products for the purpose of improving methods of manufacture and quality of product, reducing cost, and developing new products and new uses and new markets for old products. Despite frequent statements in the popular press to the contrary, the iron and steel industry is highly competitive, and each company realizes only too well that a competent technical staff is the best insurance for keeping constantly abreast of, and if possible ahead of, technical progress in the industry as a whole. Furthermore, the whole industry realizes that, despite the fact that modern civilization is built upon steel, constant vigilance is necessary to prevent undue inroads by competing materials.

The technical staff of a steel company has another duty, which is frequently overlooked; viz, the job of acting as consultant for the customer. Many small steel consumers and some large ones as well—the railroads are an outstanding example of the latter—have for many years expected the steel industry to do practically all of their development work.

For nearly a hundred years steel making and the processing of steel into finished and semifinished products has been an art in which skills of a high order have been developed. Despite the advancement of the art, there are still so many variables in the manufacture of iron and steel that even the most skilled man sometimes has to depend upon "intuition" or a "hunch" to guide him when he encounters conditions which do not fit precisely into his practical experience. The result is a lack of uniformity in quality which costs the steel companies large sums of money because of rejections by the customer. Variable quality in iron and steel has always been a problem in the industry; since about 1920 it has been even more of a problem than before, as customers' requirements have become increasingly rigid year by year.

One of the principal purposes of research by the steel industry has been to investigate the causes of erratic quality in the finished product and, by increasing technical control of the various operations, to improve the quality of the product and render it more uniform. One-third of the money spent for research has been used for this purpose.[5] One of the most common examples of the effect of research in improving quality is the automobile fender. Had anyone suggested in 1925 making the torpedo-type fender—now used even on the cheapest cars—by deep drawing sheet steel in one operation, both steel makers and automotive engineers would have questioned his sanity.

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[4] Private communication to American Iron and Steel Institute.

[5] Steel research budget for 1938 near last year's peak level. *Steel Facts*, No. 27, 4 (August 1938).

Organization of Research in the Steel Industry

Owing to the wide variation in size of the individual units of the American iron and steel industry, and to the diversity of processes and products, there naturally can be no standard of organization. In small plants, a technical staff of 2 to 20 men can handle all the routine metallurgical, chemical, and mechanical testing—and occasionally supervise inspection as well—and can plan and carry out a considerable amount of valuable research work in improving processes and materials.

The large company with a central research laboratory employs 50 to 75 men in this laboratory and frequently 20 to 50 additional men in various plants—or departments if there are only 1 or 2 plants. The large, well-balanced research laboratory—of which there are a number in the United States—employs metallurgists, physicists, chemists, mechanical and ceramic engineers, and a number of other technically trained men, one-quarter or one-third of whom hold doctorates. For example, one has a staff of technically trained men—

skilled in methods of measuring and controlling high temperature; in methods for the elucidation of the constitution and behavior of refractories and slags; in thermodynamic analysis of the chemical reactions involved in the making of iron and steel; in the methods of identification and control of the structure of steels and conversant with the relations between structure and the useful properties of steels.

Large steel-plant research laboratories act as training schools, transferring metallurgists and other technically trained men from the various plants or subsidiary companies to the central laboratory for a year or two of what amounts to intensive graduate training, thus giving these men a broad view of research as it is undertaken for the good of the company as a whole.

One of the most important things encountered in organizing and operating a large research laboratory is the choice of problems. Most directors of research adopt the general principle that the solution of the problem should be applicable to the company as a whole, leaving to the metallurgists of the various plants or subsidiary companies the problems of more restricted application encountered in their particular plant, with the proviso, of course, that the staff of the central laboratory should always be available for consultation, if necessary, even on minor difficulties.

The staff of the central laboratory of a company that makes steel also frequently cooperates on problems with the research staff of the company that fabricates the steel and of the company that uses the fabricated article. An excellent example of such cooperation is in

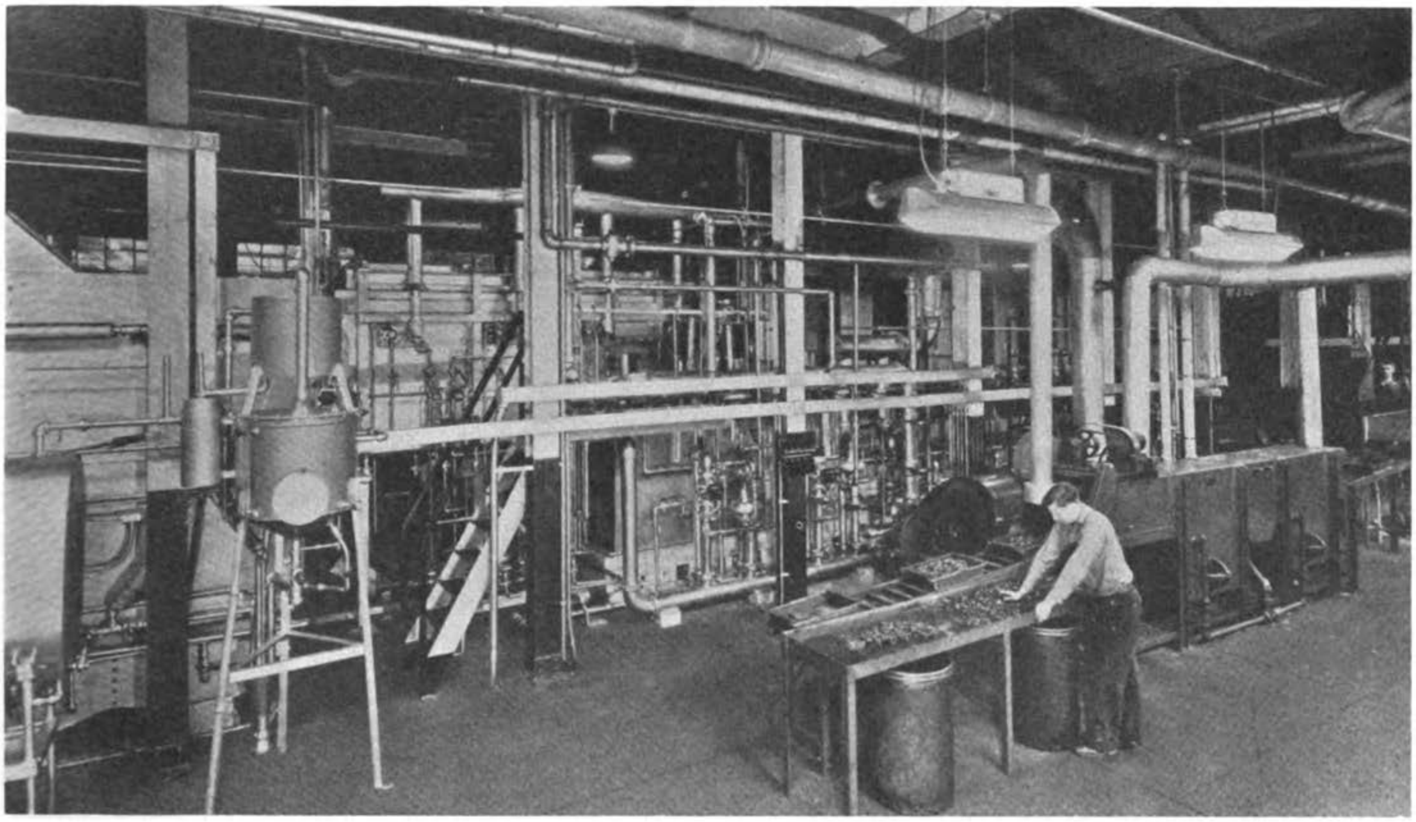

FIGURE 41.—Austempering of Steel, American Steel and Wire Company, Worcester, Massachusetts. (Subsidiary of United States Steel Corporation)

the manufacture of pressure vessels for use at high temperatures, where satisfactory service depends quite as much upon the method of fabrication and welding of the vessel as upon the melting practice used to make the steel.

Cost of Research

It is difficult to determine accurately the amount of money spent for research by the iron and steel industry of the United States. For the past 5 years or more it has averaged almost $10,000,000 annually, according to a survey recently made by the American Iron and Steel Institute,[6] which shows the following, as spent by 42 companies representing about 90 percent of the steel-making capacity of the country:

Year:	*Expenditure*
1929	$8, 700, 000
1935	8, 100, 000
1936	9, 200, 000
1937	10, 300, 000
1938	9, 500, 000

It is interesting to note that the expenditure for research in 1938 was only 8 percent lower than in 1937 despite a decrease of 60 percent in steel production. The money spent for research is distributed approximately as follows:

Project:	*Percent*
Improving quality	33
Improving methods of manufacture and reducing cost	19
Developing new products	20
Developing new uses and markets	28

The annual appropriation by individual companies is naturally not available for publication. A survey made 13 years ago[7] indicated that for 12 large steel plants the average annual research expenditure was $16,200. This is undoubtedly less than one-tenth of the average expenditure today. Actual research appropriations for 1939 by 1 large and 2 medium-sized steel companies[8] were as follows: Company A, $1,250,000, of which $950,000 was for salaries; company B, $285,000; company C, $278,000. These amounts are approximately 10 times the amounts spent by these same companies 10 or 15 years ago.

Research Personnel

The iron and steel industry employs as many as 1,000 college graduates annually,[9] over 70 percent of whom have engineering degrees. Of 593 recent graduates employed, 149 were mechanical engineers, 97 were chemists and chemical engineers, 95 were civil engineers, 70 were metallurgical engineers, 57 were mining engineers, 42 were electrical engineers, and 83 had other degrees. Of these graduates, 21 percent went into the metallurgical department, 35 percent went into open-hearth, rolling-mill, or power-generation work, 29 percent were employed in other operating departments, and 15 percent went into sales and administrative work.

Most of the large steel companies have organized plans for selecting college graduates and maintain close contact with the principal engineering schools. A number of the companies provide summer employment for likely undergraduates. There has been no lack of employment for graduate metallurgists from the country's outstanding engineering schools during the past 10 years; even in 1932–33 most graduates were placed quickly.

In general, there are fewer doctorates in metallurgy than in other branches of science; in 3 years (1934–37) 28 doctorates were awarded to metallurgists, compared with 1,449 in chemistry and 178 in agriculture.[10] During this period the same number of doctor's degrees was awarded in metallurgy as in oriental literature. The relatively small number of doctorates in metallurgy awarded at American universities is, however, no criterion of the number of scientists with doctor's degrees employed by the iron and steel industry, as many of these were trained as physicists and physical chemists.

In 1937, according to a survey made by the American Iron and Steel Institute,[11] 2,350 engineers, metallurgists, chemists, physicists, and other technical men were employed full time in the research laboratories of the steel companies. In addition, almost 1,200 other employees devoted some part of their time to research work.

Metallurgical Education

College curricula in metallurgy have not been standardized in the United States. According to Stoughton, dean of engineering at Lehigh University,[12] who studied the metallurgical courses in 22 accredited schools, all curricula included some courses in metallurgy and mathematics, chemistry, physics, and English, and most included drawing. Only 9 included a foreign

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[6] Steel research cost highest on record. *Steel Facts*, No. 13, 3 (May 1936); Steel industry intensifies its research program in 1937. No. 19, 2 (May 1937); Steel research budget for 1938 near last year's peak level, No. 27, 4 (August 1938).

[7] Davis, R. M. Research a paying investment. New York, National Research Council, division of engineering and industrial research, 1928.

[8] Private communication, American Iron and Steel Institute.

[9] Steel companies plan to hire many young college graduates in 1937. *Steel Facts*, No. 17, 3 (February 1937).

[10] Research—A national resource. 1. Relation of the Federal Government to research. Washington, U. S. Government Printing Office, 1938, pp. 172–173.

[11] Steel industry intensifies its research program in 1937. *Steel Facts*, No. 19, 2 (May 1937). There is some disagreement among authorities on the actual number of research workers, ascribable to the fact that there is disagreement on how some workers shall be classified.

[12] Stoughton, Bradley. The training of a metallurgist. (Yearbook of the American Iron and Steel Institute.) New York, American Iron and Steel Institute, 1939, pp. 79–89.

language, which was a serious handicap, as at least one-third of the reports of metallurgical research published in recent years have appeared in German periodicals. In most engineering schools, students of ferrous metallurgy spend 75 to 100 hours in a steel plant; frequently they have a good idea of the operation of a blast furnace before they even calculate a heat balance.

In 1936–37 there were 1,630 students in metallurgy in 53 colleges in the United States, out of a total of 7,190 students registered in all branches of mineral technology,[13] or nearly 23 percent. Of these, 131 were graduate students who made up 30 percent of those working for an advanced degree. Owing to a shortage of experienced metallurgists in this country, registration has increased considerably in the past 6 or 8 years; in the 53 schools surveyed by Plank, 937 were registered in metallurgy in 1933–34 and 1,630 in 1936–37.

There has been considerable discussion in recent years on whether or not metallurgical education in the United States sets as high a standard as it is reasonably possible to attain in a 4-year course. According to Stoughton, "the characteristics most conducive to success and of most service to industry which a student can gain in college and which he did not have before are judgment and self-confidence based on a knowledge of fundamentals." In this, American metallurgical education apparently has not been wholly successful, as is evident from a reading of some of the publications of the Society for the Promotion of Engineering Education.[14] The chief difficulty seems to be that the world has changed so fast that metallurgical curricula have not kept pace. It is generally recognized now [15] that in addition to fundamentals of metallurgy,

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[13] Plank, William B. Mineral technology schools continue to grow. *Mining and Metallurgy, 18*, 414 (September 1937).

[14] See for example, Collected papers of the session on mining and metallurgical engineering. *Society for the Promotion of Engineering Education, Bulletin 21*, 1-90 (March 1934).

[15] Lescohier, D. D. The place of the social sciences in the training of engineers. See footnote 14, or *Journal of Engineering Education, 24*, 414-21 (February 1934).

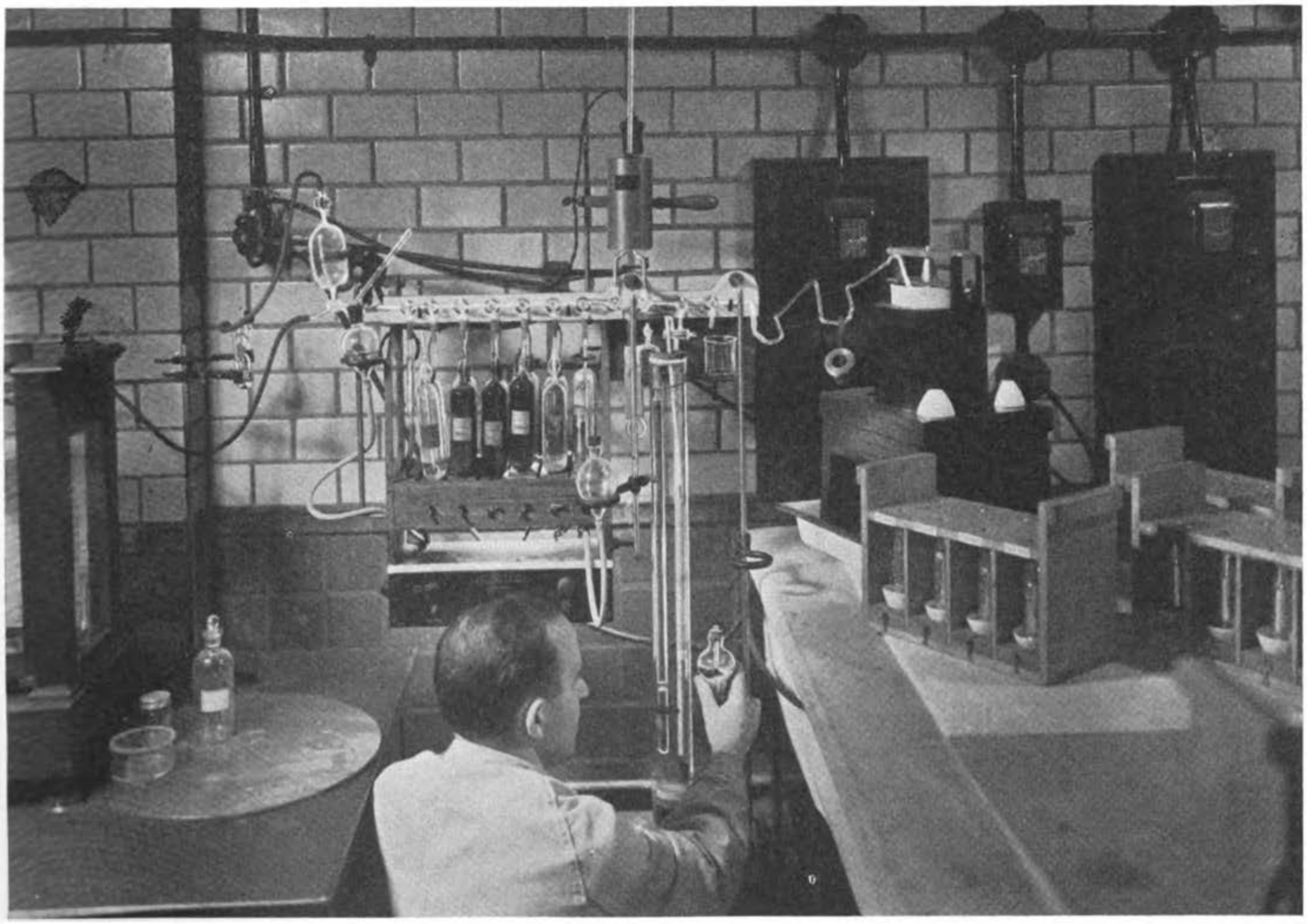

FIGURE 42.—Vacuum Extraction Apparatus for Control of Oxides in Steel, Republic Steel Corporation, Cleveland, Ohio

stressed by Stoughton, the graduate metallurgist needs a basic training in social and economic science if he is to cope adequately with any problems in the steel industry except fundamental research. How he is to attain such training in a 4-year course is at present an unsolved problem. The general aspects of metallurgical education and its relation to research are discussed in detail elsewhere [16] so that further attention here is unnecessary.

Cooperative Metallurgical Research in the Iron and Steel Industry of Germany and England

The amount of cooperative research participated in or sponsored by the American iron and steel industry has increased in the last 20 years, but it is still considerably less than that so aided in Germany and Great Britain. The organization of cooperative research in Germany and England is frequently held up as exemplary of a far-sighted program and should be outlined briefly.

According to Speller,[17] cooperative research in Germany is divided into fundamental research and the practical application of this in industry. Fundamental research is carried out by some 35 institutes, supported jointly by industry and the Government; for research in ferrous metallurgy, the Kaiser Wilhelm Institut für Eisenforschung is known all over the world. This institute, founded in Düsseldorf in 1918, is financed by the iron and steel industry through its organization, the Verein deutscher Eisenhüttenleute—only the salary of the director is paid by the Government—and the work is supervised by technical committees of the Verein, who also assign to the research laboratories of the various steel companies problems which are not suitable for the institute, and who supervise the practical application in the mills of fundamentals worked out at the institute.

Two systems of cooperative research are used in England. One, a joint project sponsored by the British Iron and Steel Institute and the National Federation of Iron and Steel Manufacturers, is devoted to research of value to the industry as a whole. Joint committees select the problems and arrange for the work to be done by qualified scientists. The Iron and Steel Institute contributes a small amount of money and affords a medium for publication; most of the financial support comes from the federation. Splendid work has been done on this joint project over the past 15 years; the best-known reports are the series on the heterogeneity of steel ingots, already mentioned, and on corrosion.

The other principal British instrumentality for cooperative research is the Department of Scientific and Industrial Research started in 1916. This is financed by the industries concerned and by the Government, each contributing about half. Publication is possible only by permission of both industry and Government. Only a small number of the problems investigated are metallurgical.

Cooperative Metallurgical Research in the Iron and Steel Industry of the United States

In the United States, most cooperative metallurgical research was, until about 1925, carried out by the various technical societies, either alone or in cooperation with industry or with the National Bureau of Standards or the United States Bureau of Mines. The most important and best-known work undertaken in this way was that on the corrosion of sheet steel in the atmosphere, by the American Society for Testing Materials, and that on the effect of temperature on the properties of metals, by a joint committee of the American Society for Testing Materials and the American Society of Mechanical Engineers. Another such valuable cooperative project is the study of soil corrosion of pipe, which has been under way for 10 years at the National Bureau of Standards with the cooperation of the pipe manufacturers. The iron and steel industry cooperated in these projects by supplying materials and the services of technical men and, in some cases, by contributions of money. There is one large endowed organization, Battelle Memorial Institute, which is equipped to undertake a variety of research problems for trade associations or individual companies—who supply most of the funds, while the institute supplies the facilities and the supervision—and its endowment permits it to undertake considerable unsponsored metallurgical research.

There are three relatively large cooperative research projects in ferrous metallurgy in this country which have received much favorable comment throughout the world. The first of these, established in 1926 and completed in 1934, was organized to supervise research in steel manufacture; this was conducted by the Metallurgical Advisory Board. Most of the funds were supplied by the steel industry; research facilities and scientific and other personnel were supplied by the United States Bureau of Mines and by the Carnegie Institute of Technology of Pittsburgh. Work done under this project on the physical chemistry of steel making has been recognized as one of the most valuable fundamental researches in steel making ever attempted.

The other two projects, Alloys of Iron Research and Welding Research, were organized by The Engineering Foundation and sponsored by the American Institute of Mining and Metallurgical Engineers, and by the American Welding Society and the American Institute of Electrical Engineers, respectively. These two proj-

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[16] Gillett, H. W. Metallurgical research as a national resource. This volume, pp. 289-305; Gibbons, W. A. Careers in research. This volume, pp. 108-119.

[17] Speller, F. N. Cooperative research in the iron and steel industry. (Yearbook of the American Iron and Steel Institute.) New York, American Iron and Steel Institute, 1931, p. 43.

ects are financed largely by industry, by research institutes, Government bureaus, and by relatively large appropriations from The Engineering Foundation's income from endowment.

Alloys of Iron Research is a project for reviewing the important research work of the world on carbon and alloy steels and plain and alloy cast irons, as reported in the technical literature of all countries, and for summarizing and correlating the data in a series of 15 monographs, of which 11 have been published. The cost of this project, which was started in 1930, is about $25,000 a year. Several hundred metallurgists have contributed enough of their time to review and criticize before publication chapters of the monographs dealing with subjects in which they are especially expert. The primary object of the monographs is to eliminate long and costly searches of the literature by research workers, to obviate duplication of research work which has been reported in obscure or inaccessible journals, and to encourage research to fill the gaps in our knowledge of ferrous materials.

Welding Research, also under the direction of a technical committee, is reviewing the literature on welding of ferrous and nonferrous materials, but unlike Alloys of Iron Research it is publishing its literature survey as frequent brief digests of a specific field. It sponsors and supervises laboratory research in welding which is being carried out in a number of universities and plants. Its budget is approximately $20,000 per year.

Contributions of the Manufacturers of Alloying Metals to Research in the Iron and Steel Industry

The several companies in the United States—and in other countries as well—which produce nickel, chromium, molybdenum, tungsten, silicon, copper, titanium, and other alloying elements, either as the relatively pure metals or as ferroalloys, and sell these materials to the iron and steel industry for the manufacture of alloy steels and cast irons have been large contributors to the advancement of knowledge in the iron and steel industry. All these manufacturers maintain well-equipped research laboratories, staffed by competent men, and carry out a large volume of important research work. Research by the manufacturers of alloying metals is directed primarily toward finding new uses for their metals, in other words toward selling more of their product. All of them, however, have a liberal policy of publication of the results of their research in the technical journals, thus inviting discussion, not only by metallurgists of steel manufacturers but also of competitors.

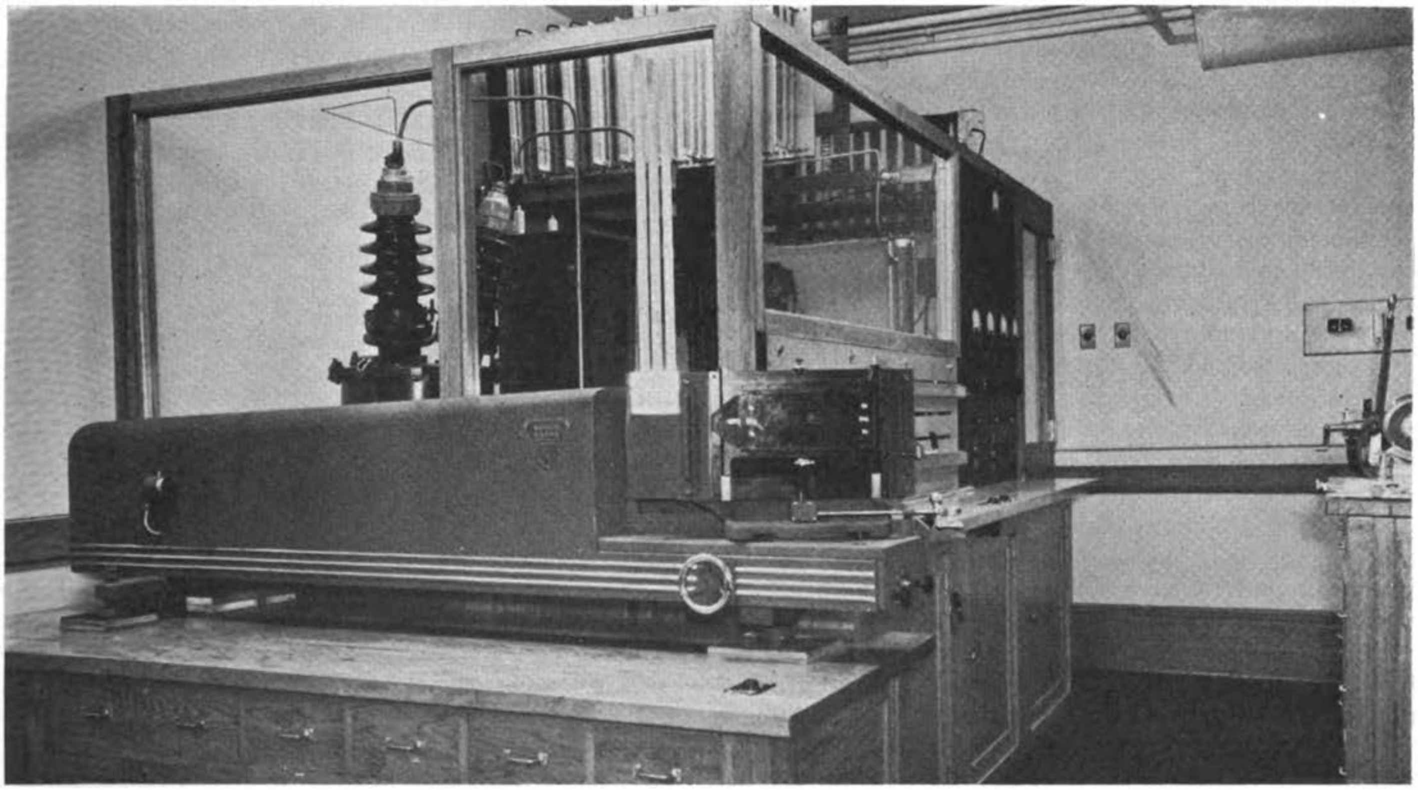

FIGURE 43.—Apparatus for Spectrographic Examination of Steel, Bethlehem Steel Company, Bethlehem, Pennsylvania

Most of the manufacturers of alloying metals publish monthly magazines which afford prompt and wide dissemination of data of value to metallurgists in the iron and steel industry. Most important, however, are the handbooks published by the manufacturers of alloying metals and by some of the steel companies. These books are unique in advertising, because they are important sources of valuable data obtained by research. The role of these publications in the American iron and steel industry is stated accurately by Gillett:[18]

> The ultimate purpose of handbooks of this type is to sell steel, and specifically the steels made by, or using the elements sold by, the firm that prepares the book. Possibly there comes in also the aspect of self-protection against complaints that would be avoided by more understanding of fundamentals and hence, more intelligent use by the purchaser. At any rate, the dissemination of sound technical information is considered so important that such handbooks have ceased to be mere catalogs and reiterations of the virtues of "Three Star Double Extra" brand, and contain not only data but discussions of metallurgical principles that are often far from being kindergarten subjects. These discussions must be brief, clear and correct, for the prestige of the firm is involved. Few text books are written with the care for correct phraseology that one meets in these books. Consequently, the student as well as the practicing metallurgist values them highly—and they deserve to be highly valued.

Research for New Markets by the Manufacturers of Alloying Metals

As noted in a previous section (p. 164), approximately 50 percent of the money appropriated for research by the iron and steel industry of the United States is spent for developing new products and new uses and markets for old products; during the past 20 years, practically all the money appropriated for research by the manufacturers of alloying metals has been spent for this purpose.

Almost immediately after it was discovered that nickel and chromium increase the strength, hardness, and resistance to impact of carbon steels, steel containing these two metals was used for armor plate and ordnance and caused a revolution in offensive and defensive naval warfare in the first decade of this century. The expanding armament programs of all nations, which culminated in the First World War, demanded such large quantities of these alloying metals, especially nickel, that the primary object of practically all research before 1920 was to increase production and to reduce cost.

Nickel production increased from 10,000 short tons in 1900 to 50,000 short tons in 1917, about half of which went into armament. With the end of the war came the collapse, and world production of nickel dropped to about 10,000 tons, the 1900 level. It became painfully apparent about 1920 that no permanent benefit would be derived, either by the manufacturers of the alloying metals or by the steel industry as a whole, from metals whose most important application was armament. As a result, extensive research was begun to find new and peacetime uses for these metals. That this research has been successful is apparent from a study of the statistics of production of alloy steels in the United States during the period (1920–35) when practically no armament was made. In 1920 alloy-steel production was 1.5 million tons, in 1937 it was 3.2 million tons, which went into automobiles, railway rolling stock, ship-building, oil-refining equipment, power-generating machinery, tools, agricultural equipment, architectural trim and building construction, electric-heating appliances, and many other products.

Between 1920 and 1937, The International Nickel Company alone spent approximately $18,750,000 in development and research to create peacetime uses for nickel.[19] During that time, the yearly production of nickel increased from 10,000 to 125,000 short tons, of which only 3 to 5 percent was used in steel for armaments between 1920 and 1935. Even in 1937, when Europe had begun to rearm on a large scale, less than 8 percent of the world's supply of nickel was used in armaments.[20] Research by The International Nickel Company and by manufacturers of other alloying metals has developed peacetime uses for their products to the point that complete world disarmament would not cause a ripple in their yearly production; it would, in fact, even be welcomed because, as Stanley pointed out,[21] "organization for war has had a depressive rather than a stimulating effect on total nickel consumption, since the loss which results from the dislocation of normal industrial routine is in no sense compensated for by the tonnage consumed in armaments."

Economic Significance of Research in the American Iron and Steel Industry

The principal advances, especially in processes and materials, that have resulted from research in the American iron and steel industry have been discussed briefly in previous sections and have been outlined in greater detail elsewhere in this book;[22] hence, only a brief summary is necessary here.

As already indicated, the first and most important accomplishment is the improvement in quality with no

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[18] Gillett, H. W. U. S. S. carilloy steels. *Metals and Alloys, 10,* MA 186 (March 1939).

[19] Stanley, R. C. Address to shareholders. The International Nickel Co., March 29, 1938.

[20] Proprietary nickel alloys. *Chemical Age, Metallurgical Section, 38,* 8 (February 5, 1938).

[21] Stanley, Robert C. The nickel industry in 1938. *Aluminum and Non-Ferrous Review, 4,* 43–6 (1938–39).

[22] Gillett, H. W. Metallurgical research as a national resource. This volmue, pp. 289–305.

significant increase—indeed in some cases with a decrease—in cost. This has been especially evident in the past decade and has affected all branches of the industry. Pig iron is more uniform in composition and quality than ever before; precision melting in the basic open-hearth process, with instrument control, with slags of carefully adjusted composition, and with regulated deoxidation to produce steels of specific grain size, is now common. New methods for exact control of the Bessemer process and for improved slag practice are being used, and good quality free-machining steel with 0.30 to 0.40 percent of sulfur is made regularly.

Improving the quality of steel without a significant increase in cost to the consumer is an accomplishment of considerable magnitude as the stricter metallurgical control necessary raises the basic cost of the material. According to White,[23] unalloyed steel containing 0.25 percent of carbon, made without modern metallurgical control and testing, cost $43.04 a ton in 1936. The same steel made with complete metallurgical control and testing, costs as much as $60.48 a ton, a possible increase of $17.44, of which $3.23 represents the cost of the metallurgical control and testing, and the remainder, $14.21, represents the increased cost of the various manufacturing operations owing to more rigid quality requirements.

The continuous rolling mill has been responsible for a reduction in the price of 20-gage sheet steel for automobile fenders from 6 cents a pound in 1923 to 3¼ cents in 1936; it has improved the quality with the result that the deformation possible in drawing a fender crown has increased from 2½ inches in 1923 to 16 to 18 inches in 1936. Today, only the nose of the fender is polished, and the paint consists of one coat of primer and one coat of finish; in 1923, three polishing operations and four priming and finishing coats were necessary.[24]

Research in corrosion and in protective coatings, and the development of alloy steels, have more than doubled the average life expectancy of all iron and steel in the last 50 years. In 1890, the average life was 15 years, in 1910 it was 22 years, and in 1935 it was 35. A considerable part of this increase is due to higher and more uniform quality, with fewer early failures.

The development of low-alloy steels, which cost between 3½ and 5 cents a pound as compared with 2½ cents a pound for unalloyed structural material, has had—and is now having—a great effect on the design and construction of railway rolling stock. A hopper car constructed of low-alloy steel weighs 30,000 pounds and carries 139,000 pounds as compared with a weight of 44,000 pounds and carrying capacity of 125,000 pounds for the conventional car. This is equivalent to converting 7 tons of dead weight into revenue-producing capacity. Savings accompanying the use of higher temperatures and pressures in power generation and in oil refining are even more spectacular and are due almost solely to the development—much of it in the United States—of alloy steels which resist deformation at high temperatures.

These are only a few of the advances in the iron and steel industry of the United States in the past 15 or 20 years which have resulted from research. The list could be extended almost indefinitely; enough has been said, however, to show that research in the iron and steel industry—which has certainly only begun—has had a strong stimulative effect on general industrial progress in the United States.

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[23] White, C. M. Technological advances in steel production. (Yearbook of the American Iron and Steel Institute.) New York, American Iron and Steel Institute, 1937, pp. 105-28.

[24] Steel makes possible new styling of 1937 model automobiles. *Steel Facts*, No. 16, 3 (December 1936); Quality of steels has increased more than price in recent years. No. 24, 4, 5 (February 1938).

SECTION IV

LOCATION AND EXTENT OF INDUSTRIAL RESEARCH ACTIVITY IN THE UNITED STATES

Contents

SECTION IV

LOCATION AND EXTENT OF INDUSTRIAL RESEARCH ACTIVITY IN THE UNITED STATES

By Franklin S. Cooper
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ABSTRACT

An extensive questionnaire survey relative to industrial research has been conducted by the National Research Council. The results have been analysed and various correlations found. A total of 2,350 companies reported 70,033 persons engaged in technical research in American industry. This is a 41 percent increase over the personnel reported 2 years ago. Slightly more than half of this increase represents real growth. The remainder is due to the increased coverage of the present survey. The current data are combined with earlier data to give an historical chart of the growth of industrial research during the last 20 years. This is amplified by a graphical representation of the "birth rate" of industrial research since 1890, showing the rapid establishment of research during the twenties but a marked slump in recent years.

The relative numbers of professionally trained, technical, and nontechnical personnel in industrial research is found to be approximately as 2:1:1. Most of the professionally trained workers are chemists or engineers.

Charts showing the research personnel in the various industries serve to illustrate the very great disparity between industries, and also the rate of growth of research within a given industry.

Correlations are established between the financial size (tangible net worth) of corporations and the number of research personnel employed. These illustrate clearly that although there are a substantial number of small and medium-sized corporations engaged in research, the total research efforts measured by number of workers, is relatively small. The bulk of the industrial research effort is supported by a comparatively small number of large corporations.

Further correlations are established between the number of research personnel and the sales or net income of corporations. If one can assume an "average company," and that the total cost of research is approximately $4,000 per man-year, the ratio of research expenditures to sales is 0.6 percent and the ratio to net income is 6 percent.

The material is presented in graphical form with a brief summary at the end.

Introduction

In this section [1] will be presented a factual description intended to answer questions as to the extent of industrial research at the present time, and as to the statistical record of its growth to present stature. The information on which the several tables and charts are based has been provided by industry itself. The data have been collected by means of questionnaires submitted by the National Research Council to all companies known to maintain research laboratories, and to a large number of other industrial organizations. The survey was assisted by the splendid cooperation of the National Association of Manufacturers, which also submitted the questionnaire to its membership. The individual returns reflect the diversity of research activity throughout the country, and illustrate, among other things, the looseness of definition of the term "research." [2]

The data collected in this way are, of course, not complete. Many organizations doing research have not been reached, nor are the returns received always comparable. However, it is believed that the coverage is quite adequate to yield a representative and qualitatively correct picture of present day industrial research.

In one respect, the information available is not precisely of the nature most desirable for the correlations attempted. Expenditures for research are usually expressed in terms of money, and it would be desirable to present the survey data in the same terms; however,

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[1] Detailed procedures of handling the data for this section will be described in footnotes, where this is considered essential to a proper interpretation of the material presented; and further, where this treatment differs from that used in the preparation of Industrial Research and Changing Technology (Perazich, G., and Field, P. M. Industrial research and changing technology. Philadelphia, Pa., Work Projects Administration, National Research Project, *Report No. M-4*, 1940). Since the report just cited contains thorough descriptions of the statistical procedures, these will not be repeated here.

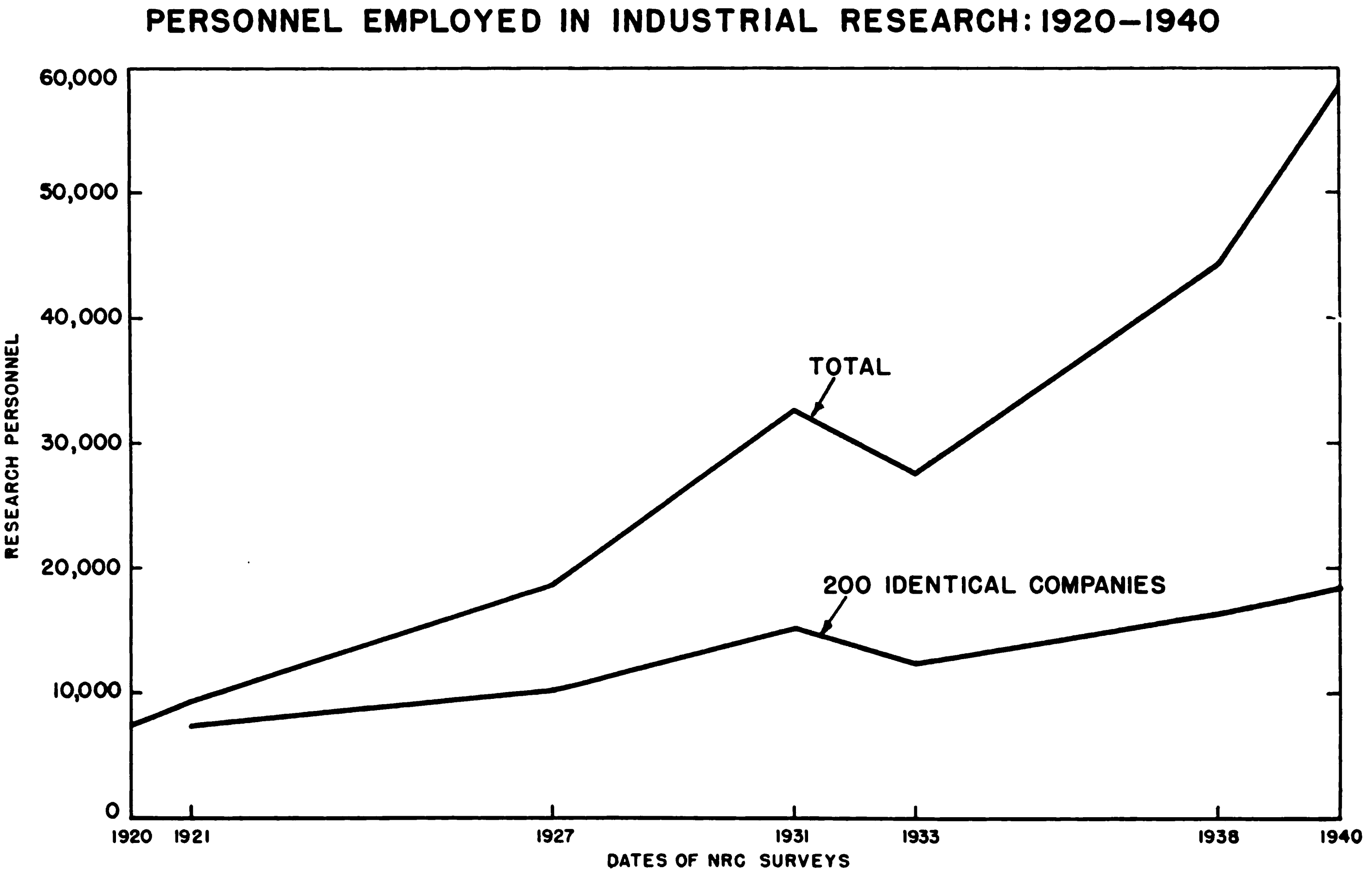
[2] The distinction between research and nonresearch personnel was left to the individual company answering the questionnaire. In some cases this resulted in the inclusion of personnel engaged in control and testing; in other cases even development engineers were excluded.

the information available from the questionnaire [3] does not permit this, and research expenditures throughout this section have been given in terms of man-years. Broadly speaking, this is translatable to dollar expenditures, although the conversion ratio will differ from company to company, and industry to industry. Several estimates of the cost per man-year of research have been made in the literature, and this subject has received some further investigation in other sections of the present survey. The generally accepted figures lie in the region of $4,000. In a few cases, dollar expenditure scales appear in the following charts, in addition to the man-year scales, but in general, it was felt wiser to present only the data as collected, and leave the interpretation to the reader.

Extent of Research in All Industries

Growth and Present Status of Research Employment

Perhaps the most significant measure of the growth of research is the number of workers enagaged in this activity. That this is so merely reflects the fact that research is a handicraft industry and, while the quality and quantity of achievement coming from any one person or from any single group may differ within wide limits, the fact remains that the producing unit is the individual worker. In a very general way, the technical training of the individual is also a secondary consideration, since the achievements which may be expected from a given group of highly specialized men depends on their being implemented by an adequate corps of technical workers. The ratio of professionally trained workers to technical assistants will, of course, vary from laboratory to laboratory, but, assuming that each



NOTE: THE UPPER CURVE SHOWS TOTAL RESEARCH PERSONNEL AS REPORTED TO THE NATIONAL RESEARCH COUNCIL (SEE HOWEVER FOOTNOTE 4). THE LOWER CURVE SHOWS THE CORRESPONDING DATA FOR A SAMPLE GROUP OF 200 IDENTICAL COMPANIES WHICH REPORTED THROUGHOUT THE PERIOD.

FIGURE 44.—Personnel Employed in Industrial Research: 1920–40

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[3] The questionnaire used by the National Research Council has been reproduced in Industrial Research and Changing Technology, p. 55. See footnote 1, p. 173. Some slight changes were made between 1938 and 1940, the principal effect of which was to modify and to extend somewhat the classes of research personnel included in the totals.

Question 8 of the 1940 questionnaire reads as follows:

"8. Total number of laboratory personnel (sum of *a*, *b*, and *c* below):

"(*a*) Number of professionally trained members of the scientific staff (including Director of Research):——.
Chemists: ——. Physicists: ——. Engineers: ——.
Metallurgists: ——. Biologists and bacteriologists: ——.
Other professional personnel (classified, if convenient): ——.
"(*b*) Other technical personnel not included above: ——.
"(*c*) Administrative, clerical, maintenance personnel, etc. ——."

In general, the classifications of research personnel reported in 1938 and 1940 are the same, except for those companies which in 1938 limited themselves to the equivalent of classes *a* and *b* of the 1940 questionnaire.

has arrived at the optimum ratio, the net achievement to be expected may still be estimated roughly from the total number of workers.

In figure 44 is shown the growth of research employment for the years 1920–40, as reported to the National Research Council. The "Research Personnel" represents the total number of employees reported as engaged in or assisting with technical research, except as noted below.[4] The upper curve relates to all of those companies which reported in the various surveys, and represents therefore an over-all figure for research employment.

The lower curve of figure 44 indicates the trend toward increased research staffs in existing laboratories. It shows the number of research employees [5] of 200 identical companies which reported throughout the period 1921–40. This group of companies contains representatives of all industrial classifications.

Both curves show a rapid increase between 1920 and 1931, a considerable drop between 1931 and 1933, and further increases between 1933 and 1940. The total for all companies (upper curve), deviates sharply from the total for identical companies during the early years, due principally to the effect on the upper curve of the increased coverage of later surveys. The over-all rate of growth between 1921 and 1940 is approximately 10 percent per year for all companies (upper curve), and 5 percent per year for the identical companies (lower curve).

The over-all growth (upper curve of figure 44) can be broken into four components: (1) The increase in personnel employed by those laboratories which have maintained and reported research throughout the period covered; (2) The increase in personnel due to the establishment of new laboratories; (3) the apparent increase in personnel resulting from the increased coverage of succeeding surveys; (4) the apparent increase in personnel due to the inclusion in recent surveys of additional classifications of research workers. Components (3) and (4) represent an apparent rather than a real growth.[6]

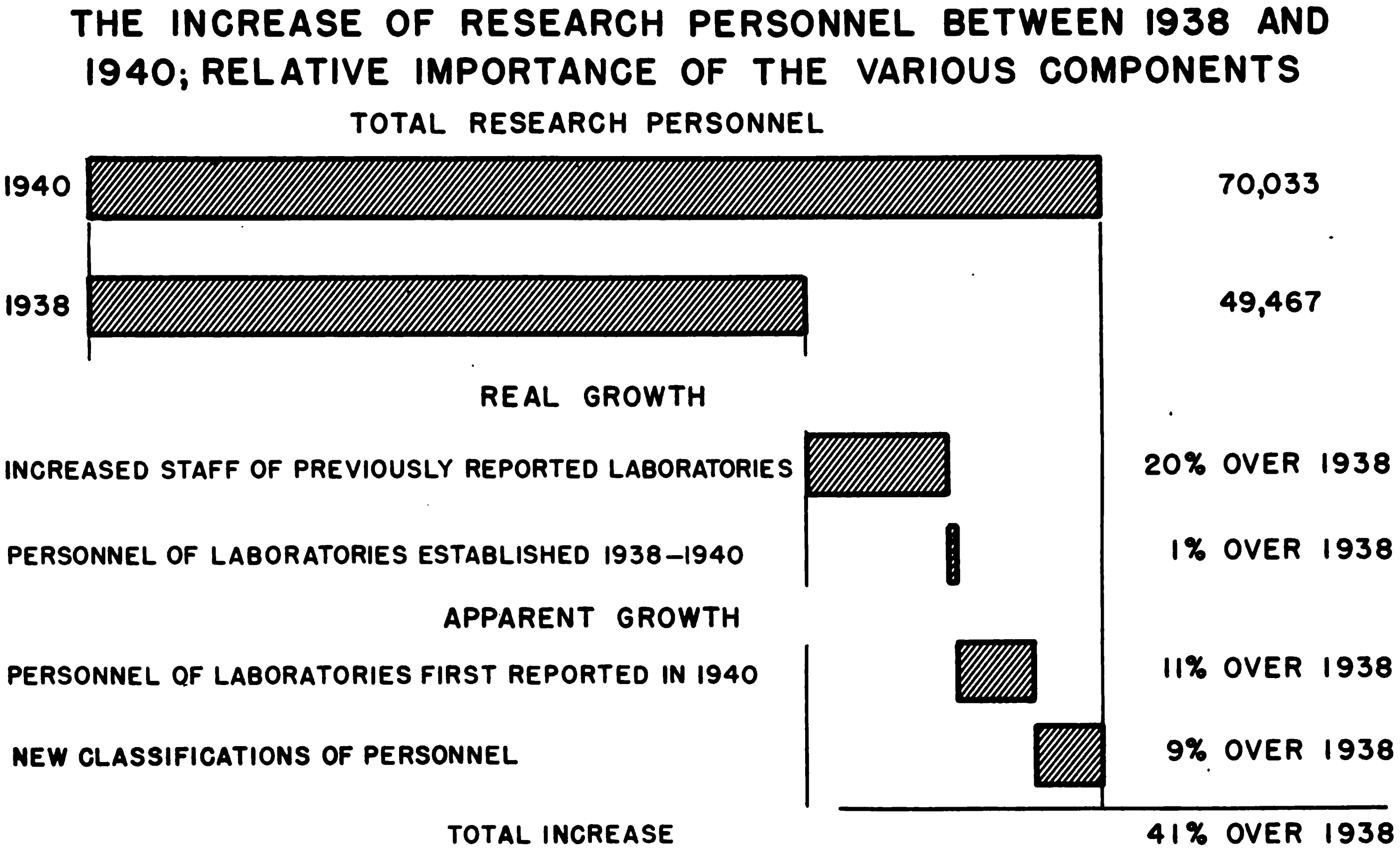

FIGURE 45.—The Increase of Research Personnel Between 1938 and 1940; Relative Importance of the Various Components

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[4] These figures are drawn from questionnaire surveys conducted by the National Research Council in 1920, 1921, 1927, 1931, 1933, 1938, and 1940. In a general way, these surveys are comparable. There has, however, been a continuing increase in the number of organizations covered, particularly during the period 1921–27. Slight changes in the wording of the questionnaire in 1938 and again in 1940 have resulted in the inclusion of previously unreported classifications of research personnel. Consequently, the data shown in figure 44 for 1938 and 1940 have been adjusted to reflect the actual growth in those classifications reported in previous surveys. This has been done by the exclusion of the classes of personnel first covered in 1938 and 1940. The resulting totals will be referred to as "comparable totals."

The data utilized in the preparation of figures 44, 47, 49, and 50 has been drawn in part or entirely from tabulations published in Industrial Research and Changing Technology (see footnote 1), which is based on the National Research Council surveys of 1920–38.

[5] The number of employees in 1938 and 1940 have been adjusted for comparability, as explained in footnote 4.

[6] However, component (4) has been excluded from figure 44. See footnote 4.

The relative importance of these four components in accounting for the 41 percent increase of research personnel between 1938 and 1940 is shown in figure 45. Slightly over half of the total increase represents real growth. It is evident that this is due almost exclusively to the increase in size of staff of existing laboratories. It might be expected that newly organized laboratories would be started with comparatively small staffs. Furthermore, such laboratories are easily missed by a questionnaire survey. Even so, the very small showing made by newly organized laboratories suggests that industrial research, considered as a resource, is not being expanded in one of the two ways in which growth might be expected, namely, the extension of research to new industrial organizations, as contrasted with the expansion of research where it already exists. This will be discussed further in connection with figure 46.

Distribution of Research Personnel by Professions

The relative importance of the various professions in industrial research is a subject of some interest. It should be of particular significance in assisting universities to guide their technically minded students into fields where there is expected to be a demand for workers. Studies on this subject have previously been made,[7] and the results presented herewith do not differ significantly, but do serve to bring the subject up to date.

Table 1 contains an analysis of the professions represented in industrial research, and shows both the number and the relative importance of various professions.[8] The very large role played by chemists and engineers is clearly significant, even though it may be debatable whether the number of chemists and engi-

TABLE 1.—*Occupational classification of industrial research personnel*

Type of personnel	Number	Percent
Professionally trained:		
Chemists	15,700	22.4
Physicists	2,030	2.9
Engineers	14,980	21.4
Metallurgists	1,955	2.8
Biologists and bacteriologists	979	1.4
Other professional	909	1.3
Total professional	36,553	52.2
Other technical	16,400	23.4
Administrative, clerical, maintenance, etc.	17,080	24.4
Total	70,033	100.00

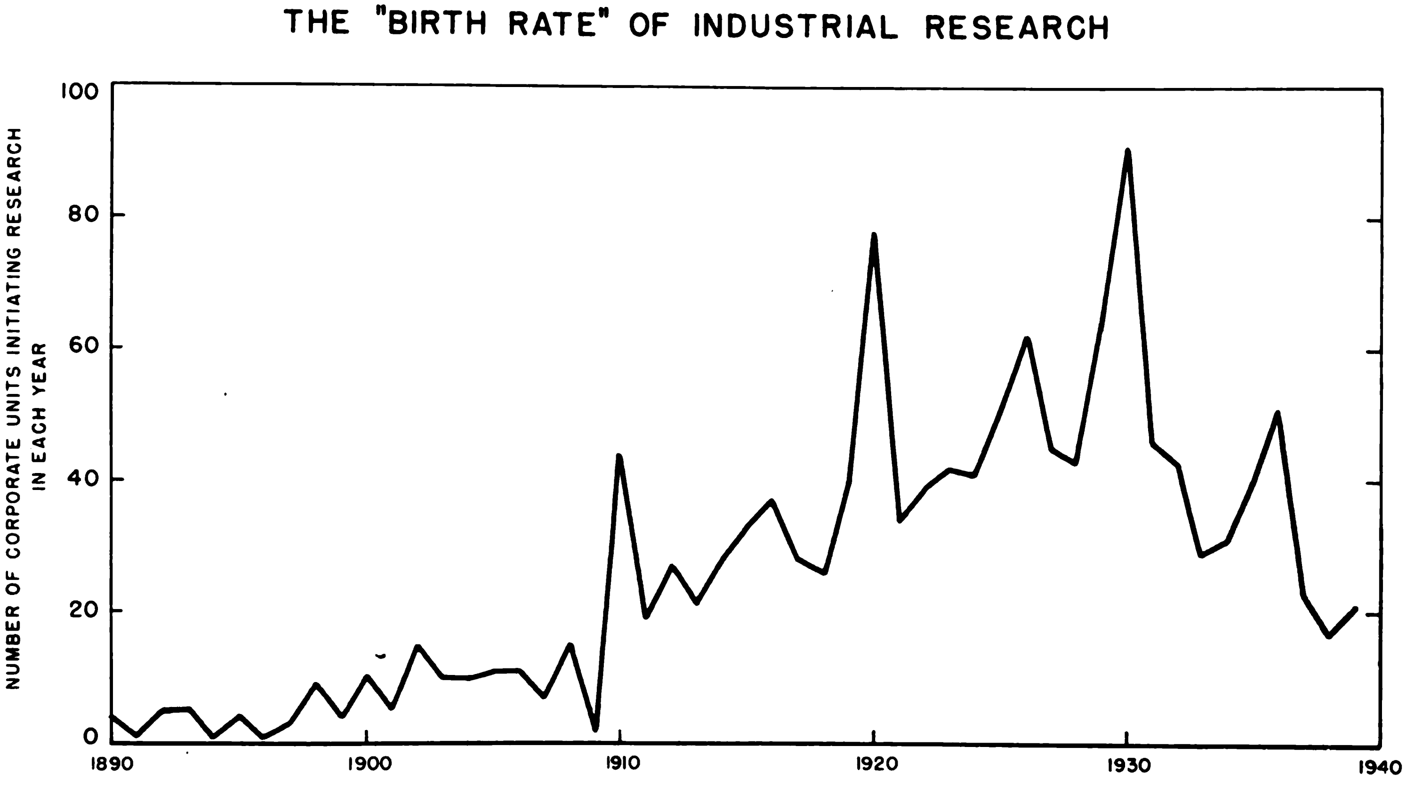

FIGURE 46 —The "Birth Rate" of Industrial Research

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[7] Industrial research and changing technology, pp. 11–14, 78–79. See footnote 1.

[8] For convenience, the number of workers in table 1 has been adjusted to equal the total number of research personnel reported for 1940. by computation from the percent distribution. The latter is based on the following representative sample: 1,699 companies employing 43,748 personnel, comprising 62.5 percent of the total personnel reported in 1940.

neers in industrial research indicates unusual opportunities in these fields or whether it represents a comparatively large supply of trained workers from which men are drawn for jobs not strictly in line with their training. It is perhaps worth noting that the total number of professionally trained personnel is in excess of the number of other technical and nontechnical people engaged in research.[9] Whether or not this represents the actual situation may be open to some question, but it does suggest that the data used for this study relate rather closely to a high grade of technical work, and that the research employment data have not been overloaded with nonresearch personnel.

Establishment of Research

If one turns from the personnel engaged in research to a consideration of the number of laboratory units involved, the data show that some 2,350 companies have reported a total of 3,480 laboratories.[10] A number of these companies are subsidiaries of other corporations and, grouping these, there are 2,210 corporate units[11] which consider research to be a recognized policy of the management.

The history of industrial research in the United States is, in large part, the history of the establishment of research by these managements. This is shown in figure 46 as the number[12] of corporate units which introduced research as a recognized function in each year since 1890. It is obvious that the character of research has varied considerably since the early laboratories were established. This should not obscure the fact that, well before 1900, a certain number of industrialists had concluded that organized technical fact-finding was a desirable activity for their organizations. Numerous cases have been reported where the original

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[9] The distribution between professional and nonprofessional personnel as shown in table 1 differs from that reported in Industrial Research and Changing Technology. See footnote 1. The difference is due principally to inclusion in the 1940 survey of classifications of research workers not included previously. See footnote 3.

[10] In this connection, "laboratory" is interpreted as the physical unit in which research work is done. Major divisions of the research activities of a large company have been counted as separate laboratories. It should be noted that the distinction between "company" and "division" is frequently merely a formal one. For the above reasons, the data given for numbers of companies and laboratories should not be interpreted too literally.

[11] I. e., The parent company together with all subsidiaries.

[12] Testing and consulting laboratories and trade association laboratories have not been included in figure 46. With this omission, the total number of corporate units reported is 1,789. Of these, figure 46 includes 1,338. The sample appears adequate to indicate trends.

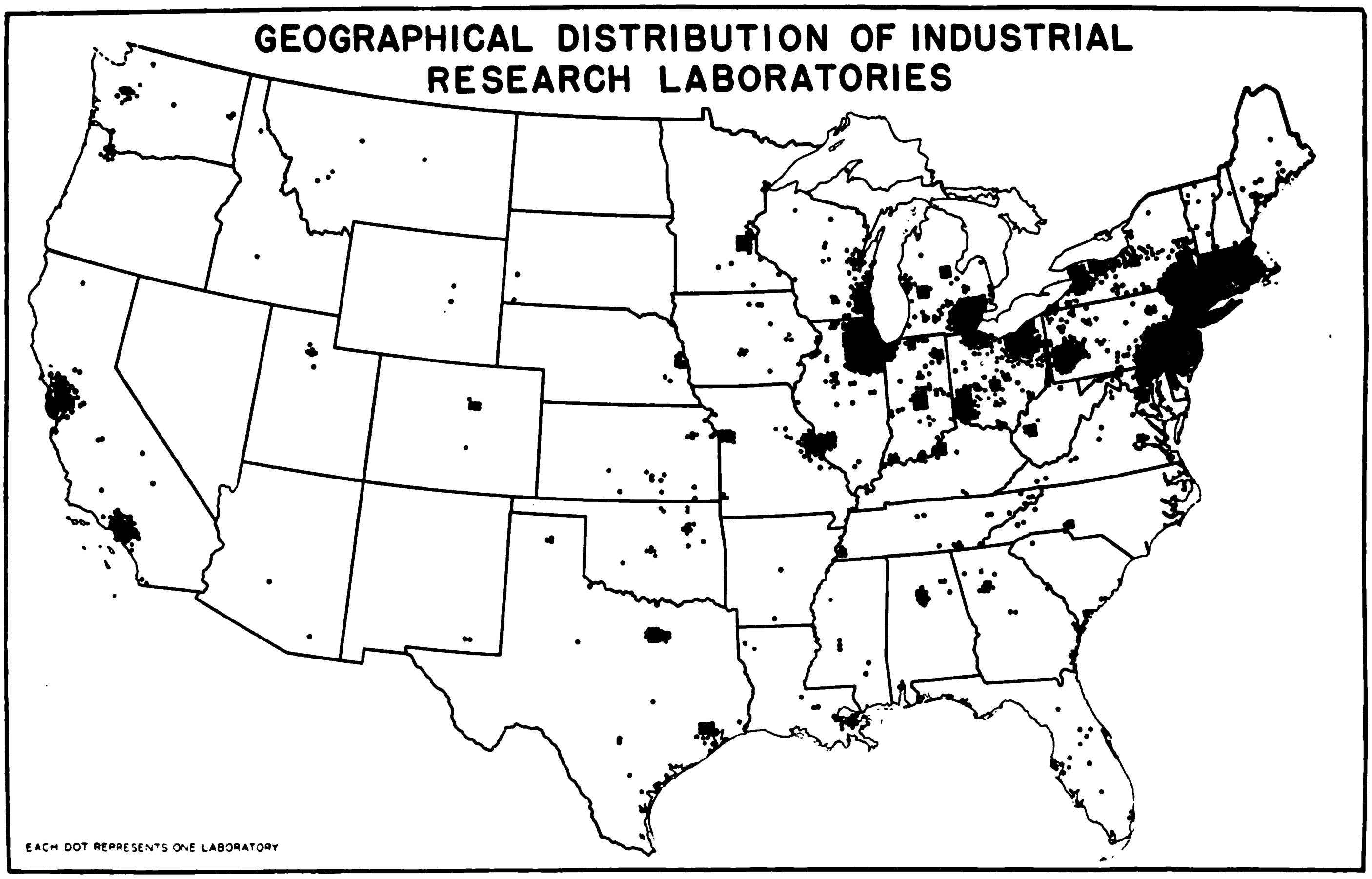

FIGURE 47.—Geographical Distribution of Industrial Research Laboratories: 1940

laboratory was little more than a raw materials and factory control group, but has since developed into a "research" group of the highest caliber. There is an unmistakable peak in the rate at which industry became research-conscious beginning with the war years, and extending into the 1930's. That this rate of establishment has dropped off in more recent years is equally apparent.[13]

The reasons for this decrease in the rate of adoption of research by new managements are not entirely clear. They may relate to general business conditions, to a saturation of the demand for research, or to entirely different causes. The trend might possibly be interpreted as a saturation of the opportunities for research, were it not for the small fraction of industry which is so engaged. In any case, here is a possible opportunity for constructive effort in broadening the base of industrial research.

Geographical Distribution of Research Laboratories

The map, figure 47, indicates very clearly the concentration of industrial research laboratories near the large industrial centers, with special emphasis on the Eastern seaboard. Each dot represents one laboratory. Divisional laboratories of the same company are shown individually wherever they are geographically separate.

Extent of Research in Individual Industries

Present Research Employment in Various Industries

A comparison of the relative amounts of research in the various industries reveals some striking contrasts. In figure 48, the individual bars represent the expenditures for research measured in man-years by various industrial groups.[14] A rough estimate of the dollar expenditures can be made by using $4,000 as an average for the total cost of research per man-year. Outstanding examples of research-minded industries are the chemical, petroleum, and electrical groups. Motor vehicles and rubber, considered together, also rank high.

Comparative Research Employment in Various Industries: 1927–1938

The rate of growth of research in the various industrial groups is shown by figure 49, which compares research employment [15] for the 2 years 1927 and 1938. This permits also an examination of the extent of research in various industries at each of these two dates. Of the industries prominent in research, petroleum shows by far the most rapid growth during this eleven year period. Radio and foods have also rapidly expanded their research staffs.

Both figures 48 and 49 represent the total research expenditure by the industry, but without considering disparity in size between industries. If one wishes to compare one industry with another on the basis of research-mindedness alone, the differences in size should be taken into account. This has been attempted in figure 50, where the bars represent research expenditure [16] as a percentage of the dollar value of the products of the industry. This is perhaps a crude method of adjusting all industries to the same base, but the errors introduced in this way are small as compared with the actual differences in the degree of utilization of research. It is interesting that some of the industries which lead in research employment drop to somewhat lower ratings when the size of the industry is taken into account, whereas other industries such as radio and stone, clay and glass appear to better advantage.

Summarizing the above data on the distribution of research by industries, the one outstanding fact is the enormous discrepancies in the extent to which research is utilized. Without question, the opportunities and the needs differ from industry to industry, but it is difficult to believe that the differences in opportunity can be so large. Moreover, the examples of rapid research expansion which have recently been set by such long established industries as food and paper indicate that the industrial research technique is widely applicable. It would appear that fertile fields for increasing the Nation's wealth might well be developed by the encouragement of research throughout the entire industrial structure.

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[13] As mentioned on page 176 the method of collecting data for this survey tends to underrate the number of small companies which have recently established research laboratories. On the other hand, the 1940 survey has gone far beyond any of the previous surveys in an attempt to discover companies not previously reported. In fact, an attempt was made to canvass all of the million-dollar (and larger) manufacturing companies in the country. Hence, it is reasonable to conclude that the small number of recently established laboratories is not primarily due to incomplete data, except in the case of companies under a million dollars (capitalization).

[14] The industrial groups follow, in general, the United States Census of Manufactures classification (U. S. Department of Commerce, Bureau of the Census. Biennial census of manufacturers. Washington, U. S. Government Printing Office). There are, however, some differences. The exact composition of the groups is discussed in Industrial Research and Changing Technology. See footnote 1. Some of the industrial groups might appropriately be consolidated, as for example, "radio apparatus and phonographs" with "electrical communication." This was not done in order to present the present data on a basis strictly comparable with that of the earlier and more detailed report cited above.

[15] In comparing figures 48 and 49 the heights of the bars of figure 48 should be reduced to the mark near the top of the bar. This is because figure 48 represents total employment, whereas figure 49 shows the "comparable totals" referred to in footnote 4. The latter totals are indicated in figure 48 by the mark on the bar.

[16] Research expenditures were computed on the basis of $4,000 total cost per man-year. This is open to the obvious objection that the figure used applies, strictly speaking, to 1940 and not to either 1938 or 1927. Even for 1940 it represents a rough average for all industries, leveling the differences between individual industries.

The choice of the dollar value of output rather than the value added by manufacture as a basis of comparison between industries is open to the same objections as the common method of expressing research in terms of sales, namely that certain industries handle large amounts of materials but perform only minor manufacturing operations on these materials, whereas in other industries, the reverse is true. This objection is valid only to the extent that research is a more valuable tool for perfecting manufacturing procedures than for effecting economies and improvements in materials.

Relation of Research to Corporate Size

Distribution of Research Establishments by Corporate Size

The research function, like many other specialized corporate activities, might be expected to require a certain minimum of financial resources before its cost could be justified. With research, however, there are numerous cases where manufacturing is a direct outgrowth of product or process development so that the research function appears in comparatively small

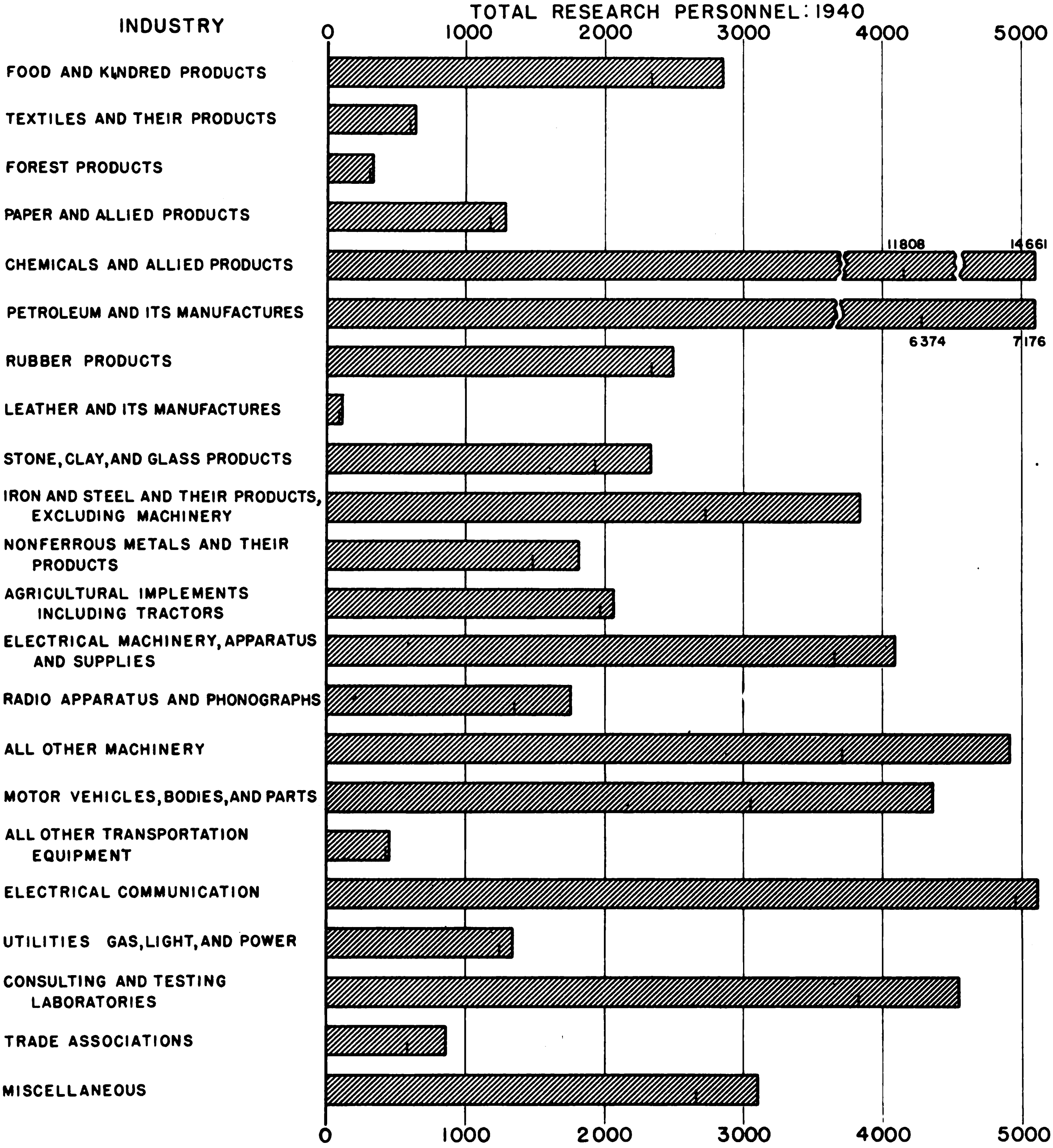

FIGURE 48.—Research Employment in Various Industries: 1940. The marks on the bars indicate values comparable with those of figure 49. See footnote 15.

organizations. Moreover, the technology of certain industries requires the services of highly specialized control and development personnel, and these are frequently reported as engaged in research.

The relative numbers of corporate units [17] [18] utilizing research are shown in figure 51, grouped according to "financial size," i. e. tangible net worth.[19]

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[17] See footnote 11 for definition.

[18] Since the research-financial relationships of commercial laboratories and trade associations differ so markedly from those of industry in general, these organizations have been excluded from figures 51 to 53.

[19] Tangible net worth ratings were derived from balance sheet data given in Moody's Industrials (1939). The rating equals net worth (reserves excluded) less intangible assets (patents, goodwill, etc.). In most cases involving subsidiary companies, the consolidated balance sheet for the parent company was used, considering this to represent the financial strength of a management which maintained research

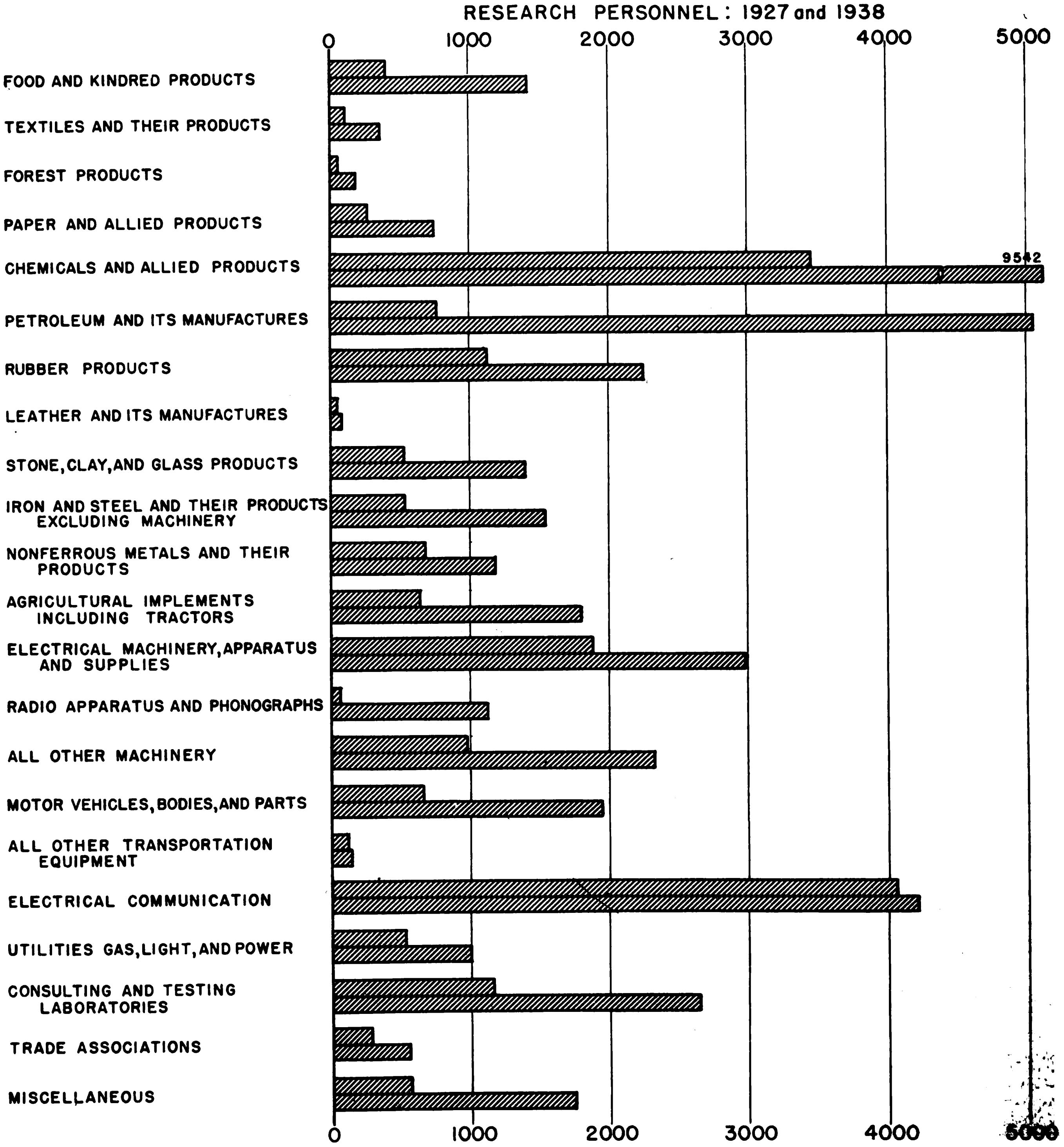

FIGURE 49.—Research Employment in Various Industries: 1927 and 1938. The upper bar of each pair refers to 1927; the lower bar to 1938

An interesting feature is the comparatively large number of corporations below $1,000,000, ranging down to $50,000, before the number decreases markedly.[20]

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in one or more of the corporate structures at its disposal. Foreign ownership was ignored, the ratings referring only to the American components.

Independent companies under a million dollars were rated from Dun and Bradstreet's Reference Book (1940), using their "estimated pecuniary strength," the equivalent of tangible net worth.

[20] The number of smaller companies is underestimated to a certain extent due to a lack of complete ratings. The data of figures 51, 52, and 53 represent 47 percent of the total number of corporate units and 77 percent of the total personnel reported in 1940, so that the distribution should be "qualitatively" correct, except as noted.

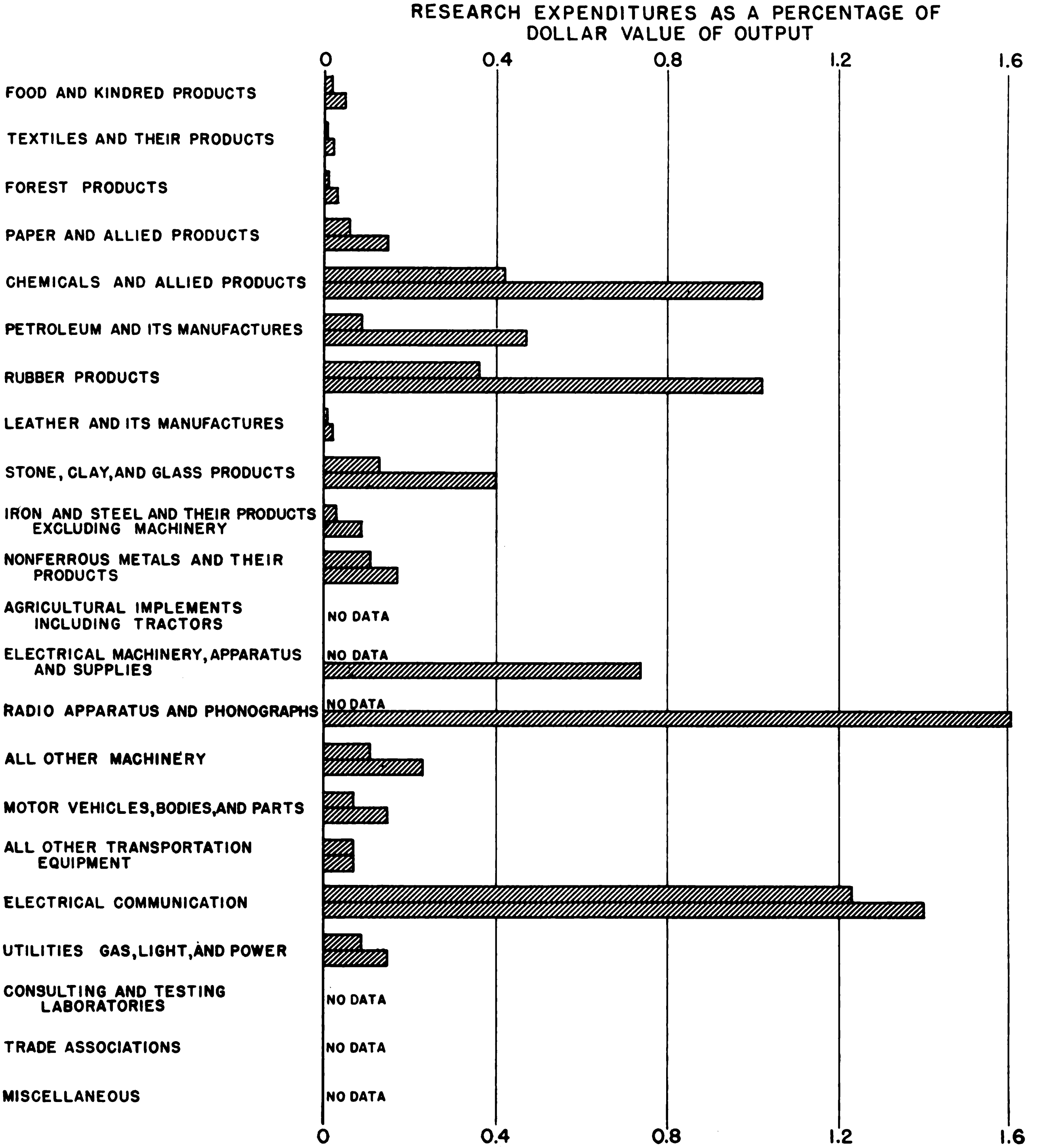

FIGURE 50.—The Percentage of the Dollar Value of Products of Various Industries Expended for Research: 1927 and 1938. The upper bar of each pair refers to 1927; the lower bar to 1938

Not shown on the figure are an additional eight companies below $2,000. Above $25,000,000 the number or organizations engaged in research drops sharply, probably reflecting the general decrease in the number of larger corporations in existence.

Distribution of Research Personnel by Corporate Size

Although the extent of research as measured by the number of managements engaged in it is a significant aspect of the size distribution, even more important is the total number of research personnel employed. The latter is not only indicative of the distribution of employment and employment opportunities; it is an index to both the expenditures for, and the achievements to be expected from industrial research. The distribution by size of industry is shown [21] in figure 52 which differs from figure 51 in that the bars represent research employment reported in 1940 instead of the number of corporate units.

The small contribution to total research employment made by the small and middle-sized corporate units is immediately apparent. Very evidently the bulk of industrial research contributions are being supported by a rather limited number of large corporations. The actual research achievements as well as the latent possibilities of the large number of smaller corporations should by no means be ignored, but the total bulk of their research effort is, at present, rather small.

Figures 51 and 52 suggest a comparison of the average number of research workers employed by corporate

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[21] See footnotes 18, 19, and 20.

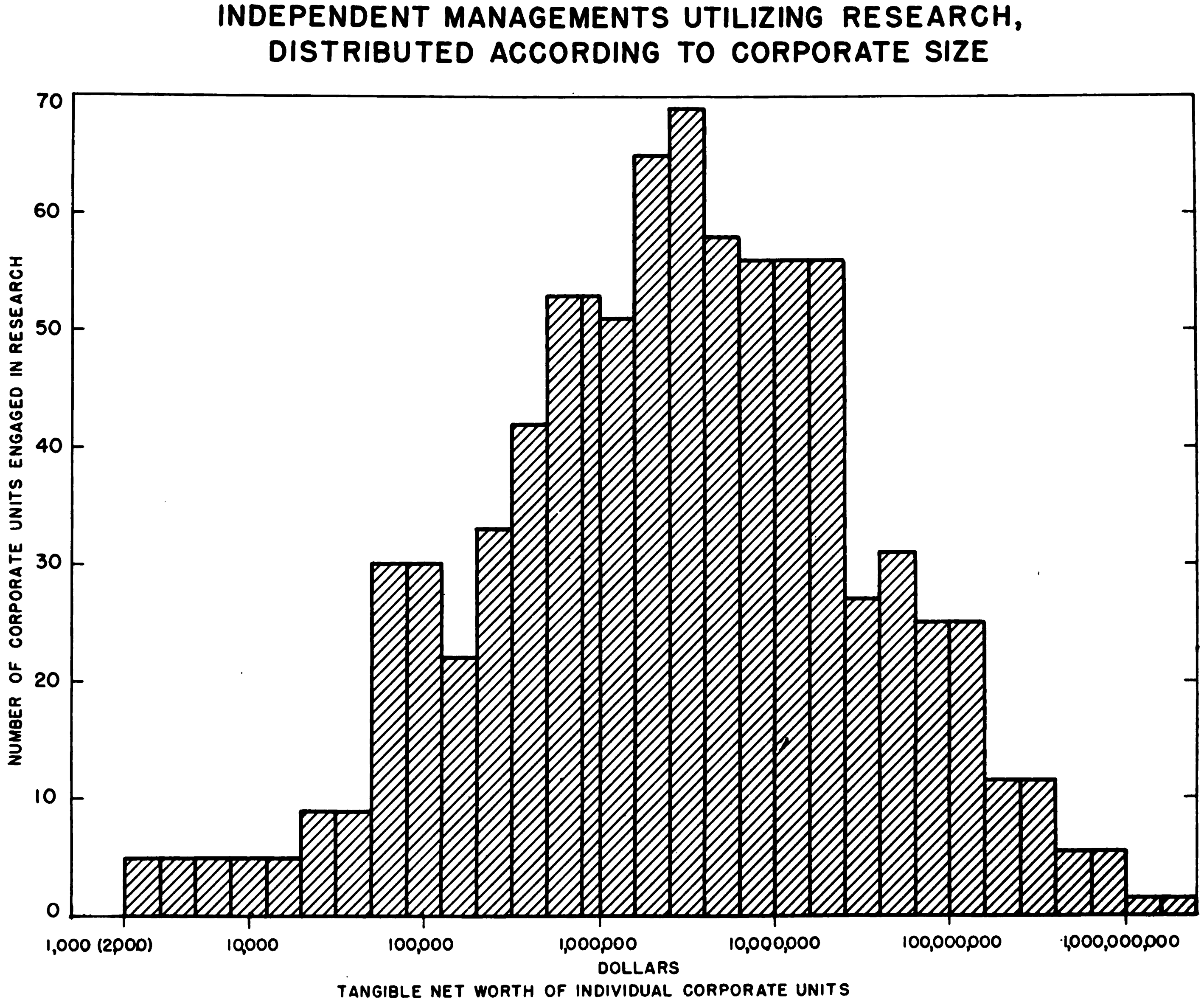

FIGURE 51.—Independent Managements Utilizing Research, Distributed According to Corporate Size: 1940

units of various sizes. This is shown in figure 53. The left-hand portion of the curve suggests the reality of an "average small laboratory" employing 6 to 10 workers and serving a company of almost any size under half a million dollars. Individual cases, of course, deviate markedly from the average. Above $10,000,000, the average research staff—and average research expenditure—increase rapidly with the size of the corporate unit, but less, however, than proportionately. Between $10,000,000 and $1,000,000,000, a hundredfold increase of corporate size, the corresponding increase in average research employment is thirtyfold.

In considering correlations such as those of figure 53, the question naturally arises as to how closely individual cases correspond to the average. Figure 54 presents the situation in the chemical industry. The curve represents average research employment versus corporate size; the individual dots correspond to total research employment by individual corporate units. The scatter of the points is indicative of the difference in amount of research done by companies of substantially the same financial strength. The correlation is rather better than might be expected in an industry so diverse in both composition and activities.[22]

Relation of Research to Sales and Net Income

As an index to the money spent for research, the ratio of research expenditures to sales is frequently used. This ratio has, to recommend it, the similarity

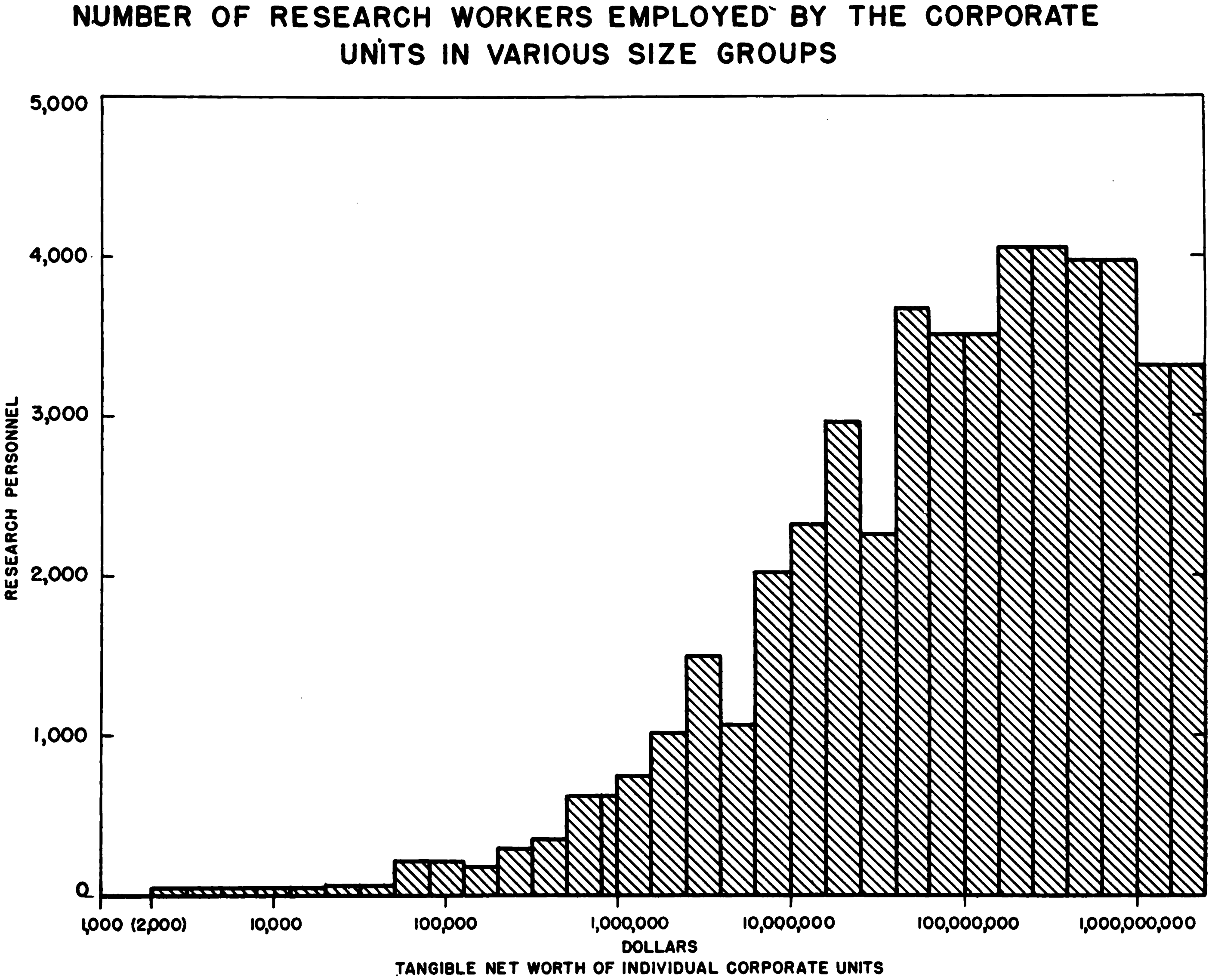

Figure 52.—Number of Research Workers Employed by the Corporate Units in Various Sized Groups: 1940

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[22] Another factor contributing to the apparent differences is the lack of uniformity in reporting technical assistants, etc., on the questionnaires. This could easily account for an apparent ratio of as much as 2:1.

to other operating ratios, many of which are based on sales. The implied assumption is that the amount of research is directly proportional to the volume of business. The data available from the questionnaires are quite extensive but research expenditures are given only indirectly in terms of total research personnel. One can, however, assume a figure ($4,000) for the cost per man-year, and thereby arrive at an approximate value for the ratio of research to sales.

Another similar index is the ratio of research expenditures to net income. This is perhaps the more significant ratio for a management considering the organization of a research laboratory, since it relates the proposed expense directly to the revenue available for its support, until such time as it shall have proved itself a justifiable operating charge.

The data[23] have been presented in figure 55 as the average number of research employees maintained by various corporate units, distributed according to their sales and to net income.

The research expenditures, measured in man-years, are directly proportional to both sales and net income over a wide range. This has been tacitly assumed before in the use of the ratios as an index figure for research. It is a little surprising, however, to find the relationships so close.

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[23] The data for sales and net income were derived from the income accounts given in Moody's Industrials (1939) and represent, in most cases, an average value for the 3-year period 1936-38. Sales represent net sales where these are given, otherwise gross sales, or, in a few cases, operating revenues, where this seemed justifiable. Net income is the income after taxes and before dividends. Subsidiaries were treated as in the case of tangible net worth. (See footnote 19.) The research employment represents the total research personnel figures for 1938. Commercial laboratories and trade associations have been excluded.

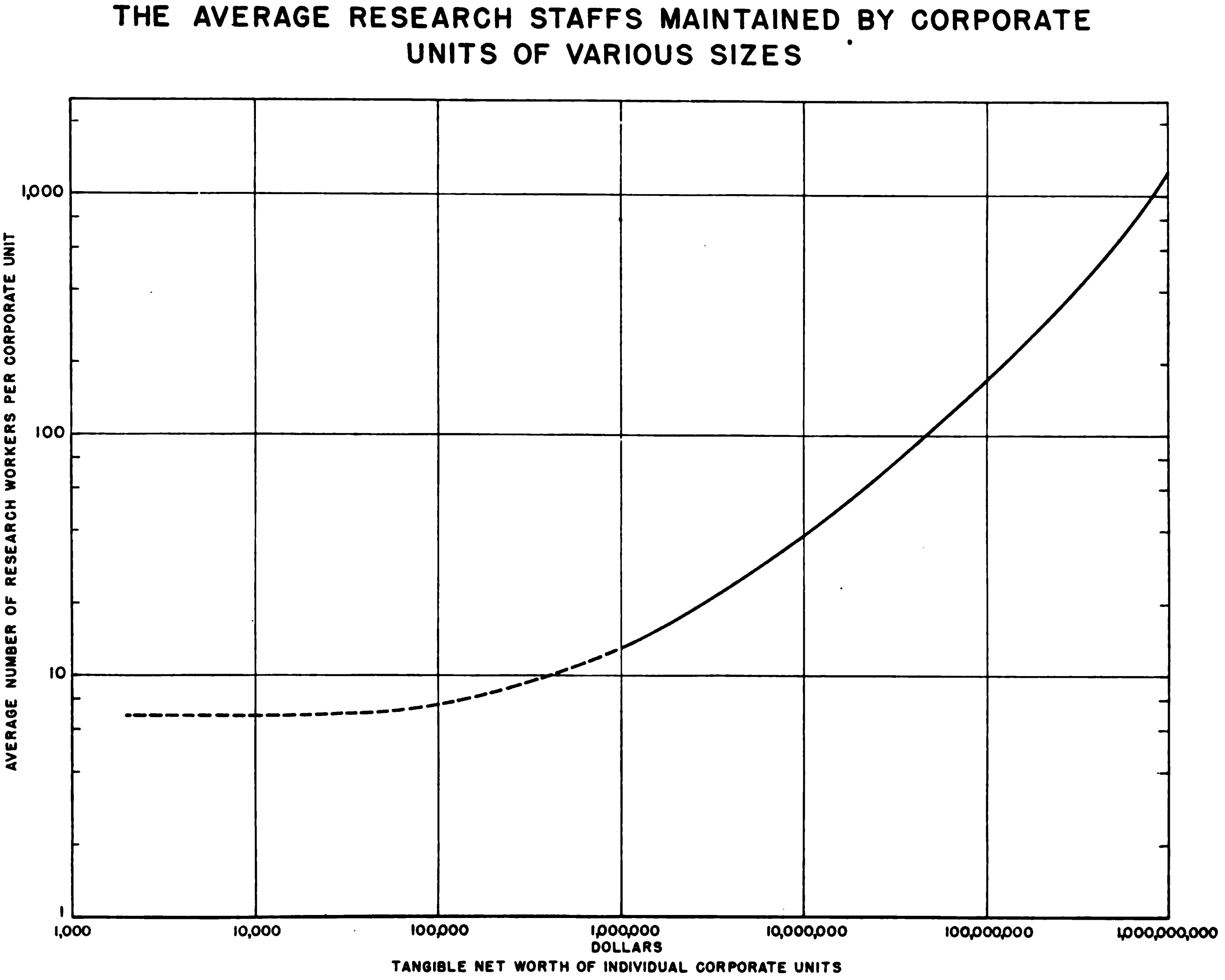

FIGURE 53.—The Average Research Staffs Maintained by Corporate Units of Various Sizes: 1940

Below sales of approximately $25,000,000 or net income of approximately $2,500,000, other considerations become the controlling factors. One does not find, as might perhaps be expected, that the above proportionality sets a rather sharp lower limit to the size of company which can or does afford to do research. Rather, there is a tendency for some companies whose sales and net income are comparatively low to maintain a small laboratory regardless of their volume of business. This almost certainly does not represent the average case for companies of restricted sales and income. However, it is of interest that in the exceptional cases where research is supported at all, the average laboratory staff remains approximately constant at 8 to 10 workers, and its size is independent of sales or income.

For the more representative cases where the proportionality holds between research expenditures and sales or net income, the percentage spent for research can be deduced on the assumption that the total cost per man-year is $4,000. The results are as follows:

	Percent
Research expenditure to sales	0.6
Research expenditure to net income	6.0

These are over-all ratios for industry in general.

Summary and Conclusions

1. A total of 2,350 companies have recently reported 70,033 persons engaged in technical research in industry in the United States.

2. This is a 41 percent increase over the personnel reported 2 years ago. Slightly more than half of the increase is a real growth, principally of the staffs of laboratories established prior to 1938; the remainder is an apparent growth, due to extended coverage of the 1940 survey.

3. The rate of increase of research personnel in industry during the last 2 years is twice the average rate for the last 20 years.

4. On the other hand, the rate at which research is being adopted by new managements appears to have fallen off substantially in recent years.

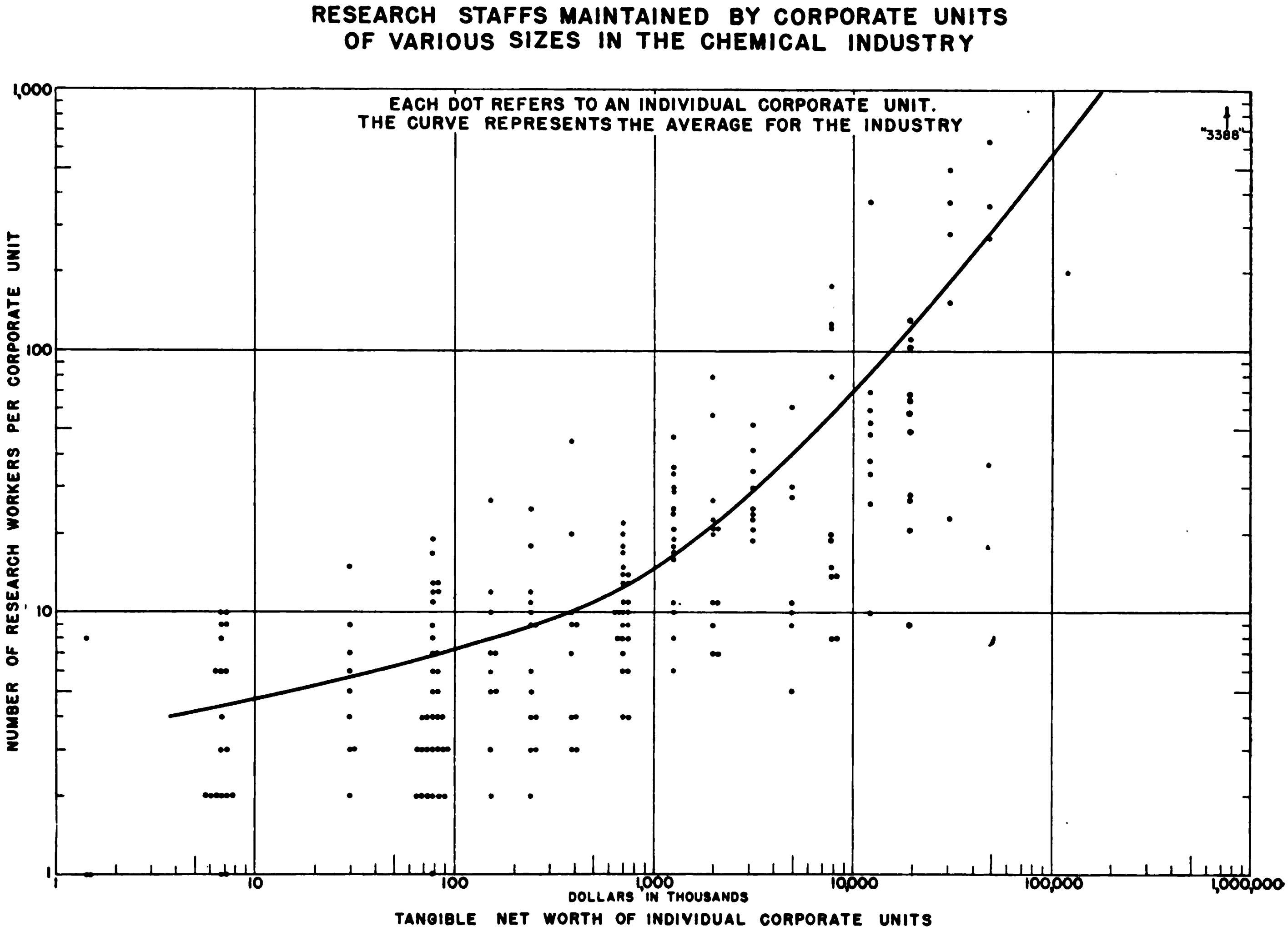
RESEARCH STAFFS MAINTAINED BY CORPORATE UNITS OF VARIOUS SIZES IN THE CHEMICAL INDUSTRY

FIGURE 54.—Research Staffs Maintained by Corporate Units of Various Sizes in the Chemical Industry: 1940

5. The contribution by newly established laboratories to the increase of research employment within the last 2 years is insignificant.

6. Of the total research personnel reported, slightly more than half are professionally trained, principally as chemists and engineers. The remainder is about equally divided between technical and nontechnical workers.

7. Comparison of the extent of research in various industries shows very great differences: the number of research employees differs between industries by more then a hundredfold in extreme cases.

8. Some industries, even these with long-established technologies have shown a very rapid rate of growth, suggesting that industrial research is more nearly universally applicable than its present use in some other industries would seem to indicate.

9. A considerable number of small and medium-sized companies conduct research. However, most of the industrial research effort, as measured by personnel, is supported by a comparatively small number of large corporations.

10. On the average, the size of the research staff is related to the financial size of a corporation as follows:

Tangible net worth:	*Average research staff*
$1,000,000	13
$10,000,000	38
$100,000,000	170
$1,000, 000,000	1, 250

11. Assuming the average total cost of research to be $4,000 per man-year, the ratio of the research expenditures of an "average company" to its sales is 0.6 percent, and the ratio to its net income is 6 percent. This is an average for all industries.

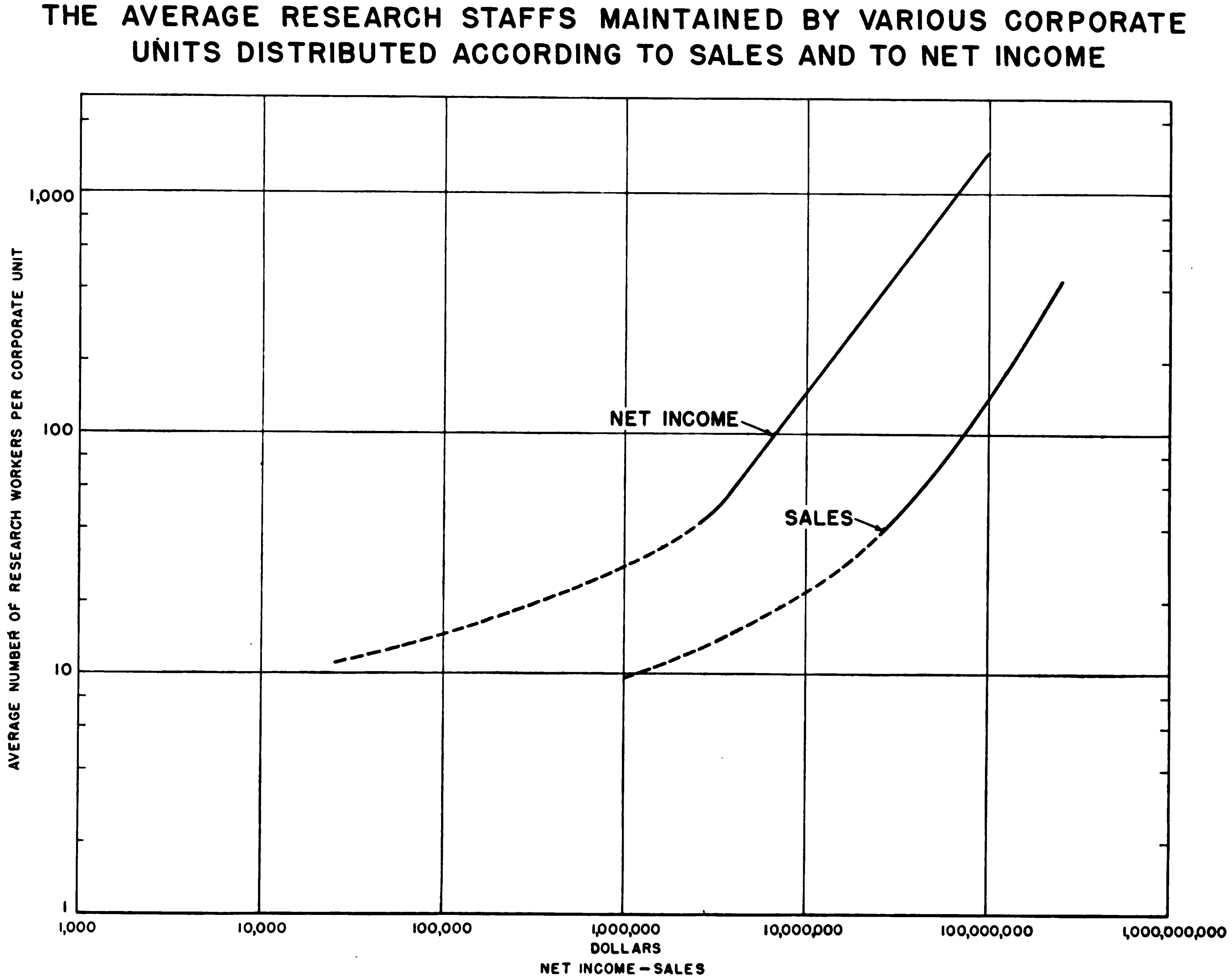

FIGURE 55.—The Average Research Staffs Maintained by Various Corporate Units Distributed According to Sales and to Net Income: 1938

12. In general, viewing industrial research as a national asset, its rapid growth in those areas where it is already established is most gratifying. The rate of expansion into additional areas appears to be decreasing rather than increasing. There remain a number of industries to which research methods could almost certainly be applied with profit on a larger scale than they now are. Finally, the total volume of industrial research being conducted by small and medium sized companies is relatively small, as measured in terms of personnel.

The above are some areas in which further investigation might discover opportunities for assisting the growth of a most valuable national resource.

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SECTION V

RESEARCH ABROAD

Contents

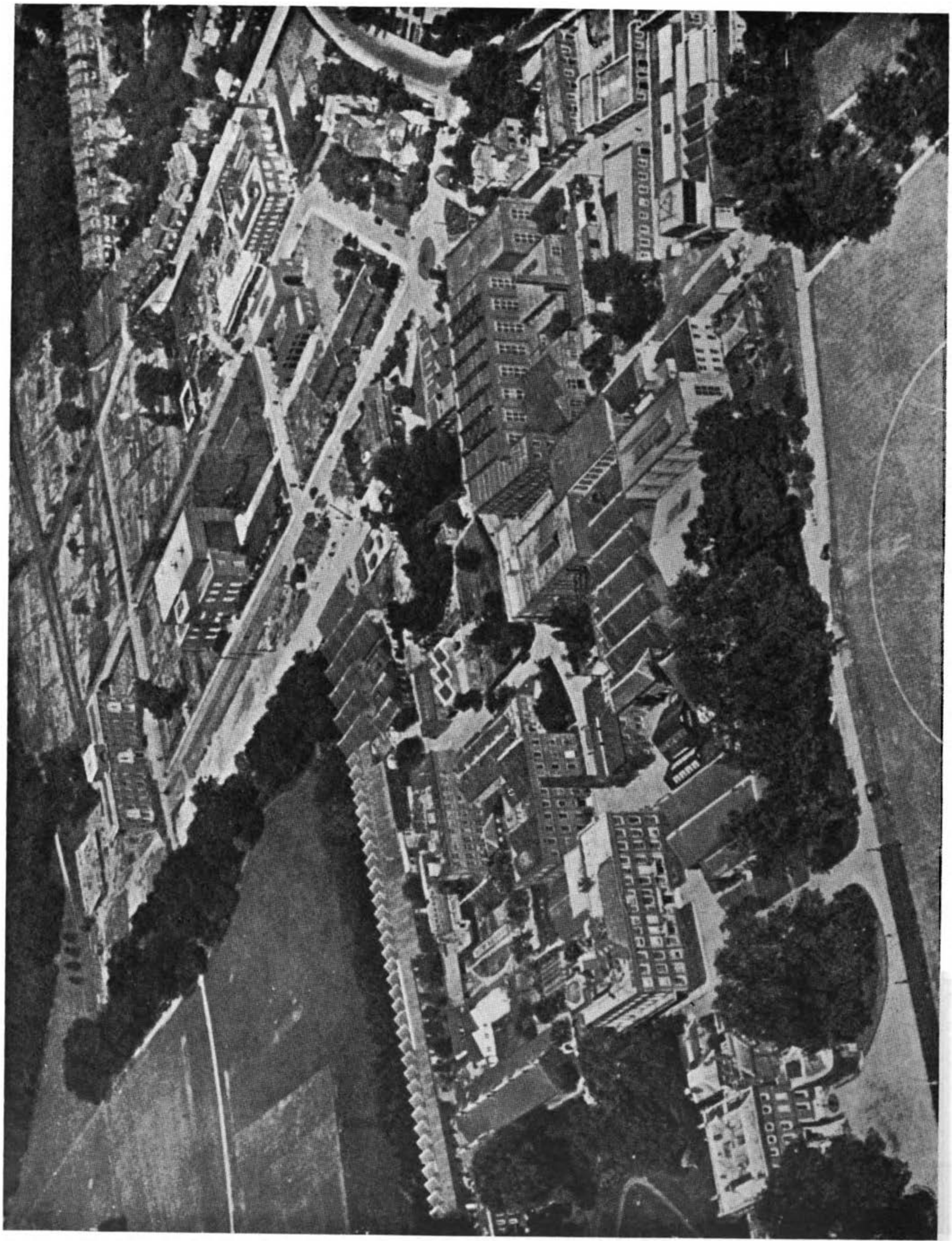


FIGURE 56.—The National Physical Laboratory, Teddington, England (after A. W. Hobart)

SECTION V

RESEARCH ABROAD

By **Dexter North**
Washington, D. C., Representative, Arthur D. Little, Inc., Cambridge, Mass.

ABSTRACT

Industrial research is being actively pursued in the major industrial nations and to a lesser extent in the smaller nations of which certain Latin-American countries have made substantial progress recently. In the totalitarian States the emphasis of research is on the national economy and preparedness. These nations also are characterized by the large extent of government support and coordination of research.

The Government of Great Britain also actively supports industrial research. Its trade association research laboratories, for which the Government matches grants made by industries, are unique among methods of supporting industrial research. Industry in Great Britain has been slow to recognize the importance of research under its own auspices but has made rapid advances in recent years.

Research in France has been better known for its accomplishments in pure than in applied science. Cooperation between industries and universities has been limited. With a few exceptions, industries have been slow in applying research to practice. Industrial research in Belgium and the Netherlands has followed rather closely the needs of their basic industries and development of colonial raw materials.

Germany was one of the first nations to recognize the importance of industrial research, which was largely responsible for the remarkable development of her industries in the quarter century prior to 1914. Close cooperation between universities and industries was an important factor in this development, the former engaging principally in fundamental research, and industries in applied research. The Institutes of the Kaiser Wilhelm Society also were of material aid to industry. Under the Nazi regime emphasis on research in all three groups was changed from fundamental work to problems of more immediate national interest. The increase in university enrollments and research, resulting from unemployment during the depression, was reversed under the program of National Socialist Government so that a shortage of research workers eventually arose. The self-sufficiency program of the Government has multiplied problems of research workers many fold.

In Italy industrial research is entirely under the control of the Fascist Government and is directed primarily toward self-sufficiency and preparedness. All new research as well as industrial projects must be approved by the National Research Council.

Switzerland has directed much of its industrial research to the needs of its specialized industries, and the development of intermediate and semi-finished products formerly imported. The Scandinavian countries have been noted for their cooperative efforts in research, and adhere rather closely to development of their own natural resources.

Industrial research was practically nonexistent in Czarist Russia. The universality of research as an important part of the Bolshevik theory has been demonstrated by the large number of research institutes built in the Soviet Union, and by the huge scope and the detail of research programs in both applied and fundamental fields. The quality of Soviet research has not been uniformly good.

Japanese occupation has dealt a crushing blow to industrial research in China. Establishment of small industries in the remote interior has been accompanied by a limited amount of research.

Japan was quick to realize the important role which research played in the industrial development of western nations and adopted these methods for her own advancement. The resulting scope of industrial research has been broad. The Japanese Government subsidizes research to a considerable extent. Many research institutes have been established, somewhat along the plan of the Kaiser Wilhelm Society in Germany. In addition to carrying forward the self-sufficiency program, the resources of Chosen, Formosa, and Manchukuo are being actively developed through research.

Canada, while relatively new as an industrial commonwealth, is advancing rapidly in application of science to industry. Certain manufacturing establishments owned or controlled by American or British interests receive the benefit of research conducted by the parent organizations. The Canadian Government has been active in motivating and directing industrial research.

Introduction

This paper describes briefly the organization and extent of industrial research, and of government and university activity in this field, in the principal industrial nations abroad. Because of the many changes in the nature and extent of industrial research which have occurred in most of these countries since the outbreak of the present war, treatment is confined for the most part to the period preceding September 1, 1939.

Portions of the statements on several countries have been drawn from unpublished reports in the files of the National Research Council. Valuable assistance both in supplying information on significant aspects of research abroad and in reviewing this paper was rendered by Dr. William A. Hamor, Assistant Director, Mellon Institute of Industrial Research, by Dr. William F. Zimmerli, of the R. and H. Chemicals Department, E. I. du Pont de Nemours and Company, Dr. Ernest W. Reid, Carbide and Carbon Chemicals Corporation, and Dr. M. J. Kelly, Director of Research, Bell Telephone Laboratories. Doctor J. W. Peter Debye, Director, Max Planck Institute, Berlin, Germany, and Visiting Professor of Chemistry, Cornell University, was exceedingly helpful in contributing first-hand information on observations of industrial research in certain European countries.

The nations whose industrial research is discussed are Belgium, France, Germany, Great Britain, Italy, Netherlands, the Scandinavian countries, Switzerland, the Union of Soviet Socialist Republics, China, Japan, and Canada. It is recognized that important industrial research is being carried on elsewhere but limitations especially of time and space have precluded inclusion of such countries. Particular mention should be made of the recent considerable expansion of industrial research in Latin-American countries, notably Brazil. Australia, New Zealand, India, and South Africa are also reported active in industrial research.

Outside of the United States research has been conducted most actively in Great Britain, Germany, the Union of Soviet Socialist Republics, and Japan. Opinions differ as to how these nations should be ranked in industrial research. No attempt has been made to give such a rating nor to compare the research standings of these countries with that of the United States.

It is indeed significant that three of the four foreign nations most active in research are totalitarian states. It is even more significant that the research policy of each has been concentrated on self-sufficiency and preparedness. Under conditions existing in the world today the influence of such policies on future research may well be profound.

Industrial research in the principal foreign countries differs in other respects from that in the United States. In contrast to the virtual absence of coordination and complete freedom from governmental control of research in this country, coordination and government control has been carried to the highest degree in Germany, Italy, the U. S. S. R., and Japan. Such a policy has been the natural development of totalitarian philosophy. Although it may eliminate duplication and assist in concentration of efforts on matters of national import, it can scarcely be said to encourage freedom of activity on the part of the individual research worker, or to promote the best interests of pure science.

In all countries industrial research has been done confidentially, but in varying degrees. The principal difference has lain in whether research results which were not patentable or which must be maintained confidential because of their nature were not published at all or were published after adequate patent protection had been secured. Results of industrial research have been published more openly and freely in the United States than elsewhere. Other differences in degree of privacy of industrial research have existed in restraints imposed on attendance of research workers at scientific and technical meetings, and in general in the willingness and freedom of researchers to discuss their problems.

The cartel system, as practiced internationally, has been cited as a restraining influence on industrial research by reason of its tendency to produce more or less static conditions in an industry. Markets and prices are usually fixed; hence profits are less dependent on advances made through research.

Exchange among nations of scientific and technical information in applied fields has been fostered in indirect ways, principal among which have been meetings of international societies and congresses such as the International Union of Pure and Applied Chemistry and the World Power Conference; wide circulation of scientific and technical publications in countries other than those of publication; services of government and industrial agents in foreign countries; issuance of patents; and more recently through licensing abroad of processes and manufacture of new products. The International Union of Pure and Applied Chemistry, an outgrowth of the International Congress of Applied Chemistry, has for its purpose the encouragement of international chemical science and the fostering of knowledge in industrial chemistry. Many notable papers have been presented at its sessions.

Research in Belgium

Science in Belgium has traditions dating back to the great period of the seventeenth century. The course of science in Belgium, unlike that of many of her continental neighbors, has been influenced not by that of Germany, but by that of France and to a lesser degree of England.

The National Foundation for Scientific Research, the universities, and private organizations have been the principal agencies conducting research in Belgium. The Foundation is an outstanding example of the impetus given research by the Belgian Government in recent years. Let us consider first the activities of Government in research, either through direct participation or indirect inspiration; then in turn consider the work of educational and industrial organizations.

The Belgian attempt at government research or government subsidized research was largely inspired by the successful plan of the Department of Scientific and Industrial Research in England. King Albert was the first to give national emphasis to the importance of scientific research. His eloquent appeal in 1927 for the foundation of a national research institute resulted in the formation of the National Foundation for Scientific Research (Fonds National de la Recherche Scientifique) with a capital of 120 million francs (about $4,000,000) subscribed to by banks, industrial and commercial organizations, and private individuals. Although the Government did not lend financial assistance, it sponsored the scheme.

The Foundation has been actively and exclusively concerned with basic research. Assistance to industry has been limited to scientific investigations susceptible of promoting industrial development, thus excluding work directed primarily to perfection of industrial processes. The principal fields investigated in recent years by the National Foundation have been: Disinfection of plants; production of new varieties of flax; behavior of metals at high temperatures; hydrogenation of coal tar for production of fuel and lubricating oils; production of phenolic resins for insulating purposes; rubber vulcanization to avoid scorching; study of the viscosity of drawn glass leading to improvement in the manufacture of window glass; alloys; Diesel motors; electric welding; wireless telephony; leather; brewing; adhesion of enamels; electrochemical chlorination of benzene. Profits derived from these researches are said to have considerably exceeded the subsidies granted for their undertaking.

Several commissions and committees coordinated the work of the Foundation with that of university, industrial, and national agencies. The Commission Science-Industrie, with an annual budget of 1,000,000 francs (about $33,000) examined over 1,000 applications and granted 86 research subsidies in the first 10 years of its existence, representing a total of 6,564,760 francs ($215,000). It also passed upon subsidies for scientific research granted by the Office de Redressment Économique (OREC).

A plan for Government participation in scientific research was initiated in 1937. The OREC was established to aid economic recovery and was empowered among other duties to grant subsidies for research to industrial or agricultural concerns. Thus research bearing more directly on industry was dealt with by the Government, and scientific research by the National Foundation.

Following revaluation of gold holdings a 15 million franc credit was allocated for research over a 5-year period, of which 5 million francs was for scientific research, and 10 million for the creation of national institutes and laboratories of industrial research, the performance of technical tests, and for the issuance of certificates. Beneficiaries of subsidies were required to match the amount of any subsidy granted. By the end of 1938 the Government was faced with such financial and political difficulties that no further credits for research were granted and OREC ceased to exist. Feeling existed in some quarters that the increased governmental activity was tending toward nationalization and that research was a means to this end. State controlled research was not well received by industry and abandonment of Government effort was viewed with satisfaction.

The only laboratory established of several contemplated with funds earmarked from the gold revaluation was the National Silicate Laboratory, a nonprofit organization for testing raw materials and finished products of the Belgian silicate industry. Of the original subsidy of 1 million francs, half was for a building and equipment and half for an operating fund. The laboratory endeavored to replace empirical methods in manufacturing with scientific control. All projects were treated anonymously, and although results were not published, they were widely disseminated among members. Firms receiving material benefits from such research were expected to reimburse the laboratory for expenses incurred in their behalf.

Fifteen research subsidies totaling 1,500,000 francs ($49,500) were approved by the Commission Science-Industrie and the OREC between August 1937 and June 1938, when the latter went out of existence. The principal investigations carried on concerned: Dielectric properties of insulating materials; mechanical stresses in pressure vessels, and standards for machine tools; fruit preservation on an industrial scale; classification of Belgian arable land; pilot apparatus for measuring radio interference from electrical devices; properties of Belgian clays; nutritive value of special fodders; disinfection of plants and soils.

The Ministry of Economic Affairs maintained an establishment for testing firearms, research in ballistics, and other scientific work, which was open to use by firearms manufacturers. Late in 1939 the Ministry of National Defence established a Bureau of Scientific Research to serve as a liaison organization between the National Defence Department and the research establishments of universities and industries. Thus much of the work in research in Belgium in recent years has been undertaken, or at least greatly influenced by the Government. Let us now briefly consider the work of other agencies—foundations, universities, and industrial organizations.

La Fondation Universitaire was founded in 1920 for the advancement of science, but more specifically for aiding Belgian students of insufficient means to enter institutions of higher learning, and to the development of scientific methods in industry, giving support to scholars, researchers, and students of demonstrated ability.

The Fondation Francqui was established in 1932, for development of advanced education in Belgium, complementing in this respect the Fondation Universitaire and the National Foundation for Scientific Research. One of the aims of the Belgian-American Educational Foundation, Inc., was to assist scientific research.

Since it was primarily an industrial country, it has been necessary for Belgium to be progressive in order to compete successfully with other nations. Compared with several European countries, it has been more favorably situated with respect to foreign exchange and therefore has been able to import substantial quantities of raw material for conversion into finished products.

Research by Belgian industry was similar to that in France, the industries being basic in nature with little departure from them. Some work was done on materials of the Belgian Congo, notably copper, radium, tantalum, and copal. Technology was probably more advanced than in France. Secrecy concerning new developments was the usual practice but perhaps less extreme than in France. Applied research in general was not well advanced.

Union Chimique Belge, Société Anonyme, largest chemical company in Belgium, engaged in considerable applied research, but information on whether or not it did fundamental research is lacking. Well equipped research laboratories were also maintained by numerous other industries and groups, including:

Comité Électrotechnique Belge.
Laboratoire de Recherches du Groupment Professionel de Fabricants des Ciments Belges.
Société Financier des Transports et d'Entreprises Industrielles.
Société Belge de Germanique.
Société Belge de Radiophonie.
Solvay et Cie.
Société Belge de L'Arête et des Produits Chimiques du Darly.
Établissements Englebert.
Ateliers de Contructions Electriques de Charlerei.
Société Nationals des Chemins de Fer.
Les Produits Organique de Tirlemont, S. A.
Raffinerio Tirlemontoise.
Société Anonyme des Usines Remy.
Usines Duché.
Fabrique de Soie Artificielle de Tubize.
Société Général Métallurgique de Hoboken.
Société Belge de l'Azote, Ougrée.

The principal fields of industrial research included glass, metallurgy, metallic carbides, heavy chemicals, glue and gelatin, copal. Research in inorganic was considerably more advanced than in organic chemistry.

Some of the industrial laboratories have cooperated with universities, notably in electrotechnology, civil engineering, and microchemistry. As previously described, the National Foundation for Scientific Research gave financial assistance to industries for the study of scientific problems of expected benefit to the national economy.

Research in France

France has a glorious history of the development of the physical and biological sciences and has produced many famous scientists. The great age of her science commenced in the seventeenth century, survived the Revolution and reached its height during the Napoleonic era when it undoubtedly led the world. But in comparison with other nations this progress has not been maintained, owing perhaps to the narrow outlook and lack of support by the various governments.

The First World War and the subsequent depression dealt severe blows to science, and in fact exerted the opposite effect of that in Germany and, to a less extent in Italy. The examples of these nations, however, served to awaken scientists, industrialists, and statesmen to the importance of science and research in the economic recovery of the country. New institutes were founded, the needs of French industry, and the requirements of national defense were recognized, all of which required much larger financial aid on the part of the government, industry, and individuals than had previously been given.

The development of science and scientific research in France has always been uneven and spasmodic. Progress has mainly been due to the self-sacrifice and the detachment from industrial considerations of the investigators themselves. This detachment, coupled with the temperament of the French people, has resulted in the country falling behind in the application of scientific discoveries to industry. It has been said that a French scientist forgets an investigation on its completion in his interest to commence the next.

Government

Although the scheme for reorganization of science in France had not been completed when the present war began, two principal sections of Government controlled research had been officially instituted—Le Service Central de la Recherche scientifique and Le Centre National de la Recherche scientifique appliquée, which dealt with fundamental and applied research, respectively. Each body was directed by a Conseil superieur, the members of which consisted of eminent scientists and representatives of interested ministries. An haute comité directly responsible to the Minister of Education coordinated the work of the two organizations, which were financed both by the Government and by levies on industry.

Le Service Central de la Recherche scientifique created a group of workers whose principal function was research and who were assured both of advancement by a plan similar to that in universities, and of economic security. Its duties were advisory, coordinating, and financial. It planned projects and brought together resources and directors for projects. Senior research workers directed the research projects. Under its auspices have been established the Astro-Physics Service, the Large Scale Chemistry Laboratory, the Atomic Synthesis Laboratory, and the Institute for Textual History. The previously created Magnetic Laboratory and the Physical Institute have been reorganized.

The Centre National de la Recherche scientifique appliquée was established by decrees in 1938, one of which stated its purpose as follows:

> 1. To facilitate scientific researches or undertakings of interest to the national defense in establishing all possible links between the research services of the corresponding ministries, those of national education, and eventually, qualified private organizations.
> 2. To contribute to these researches or undertakings by initiating, coordinating, or encouraging applied scientific research carried out by the research workers in the service of the Ministry of Education, or eventually, of private organizations.
> 3. To carry out all justifiable researches for which cooperation shall be asked by private enterprise or by individuals.

The Centre National was composed of the following 20 divisions:

Water power.
Mines.
Agriculture and fisheries.
Metallurgy.
Chemical industry.
Utilization of fuel (boilers, steam engines, motors, etc.).
Machinery.
Textiles, wood, and leather.
Building construction.
Lighting and heating.
Physical education and sport.
Civil engineering.
Transport.
Communications.
National defense.
Printing, cinemas, etc.
Light industry, furniture, and domestic engineering.
Hygiene.
Nutrition.
Working conditions.

The Office National des Recherche scientifiques et industrielles et des Inventions was created in 1922 as successor of the Direction des Recherches scientifiques et industrielles et des Inventions, to foster research required by the public services, to encourage inventions, and to coordinate public and private research in the interests of industry. It rendered valuable services until the time of disbandment recently. Its functions have presumably been transferred to the newly organized Centre National de la Recherche scientifique appliquée.

In the highly unified State which is France, the educational system is administered from a central authority, although not all the State-subsidized educational establishments are under its direction. A principal group in this system are the advanced technical schools, part of which are financed and regulated by the Government. Among the most important of these are the Grand Écoles such as the École Polytechnique which is attached to the military establishment, and the Écoles des Mines and Écoles des Ponts et Chaussées, which are attached to the Ministry of Public Works. The Ministry of Education has charge of the 17 State universities and supervises the various learned societies such as the Academy of Science which is within the Institute de France, the Academy of Paris, of Medicine, of Surgery, and the Regional Academies. The Ministry provides subsidies for these academies as well as for other organizations under its supervision or direct control. Subsidies are also provided for scientific missions abroad. In addition there are a limited number of privately endowed institutes, such as the Institut Pasteur. The research laboratories of the Collège de France in Paris has been conducting outstanding research in physical, organic, and inorganic chemistry.

The Ministries of Public Health, Public Works, Commerce, Merchant Marine, Posts, the three defense ministries, and the Ministry of the Colonies each maintain special laboratories, and in certain work make use of laboratories of other departments. Certain specialized technical schools, and the laboratories for the government monopolies on tobacco, matches, and explosives, also come under the jurisdiction of some of these ministries.

Endowed Institutes

Several endowed or semiendowed research institutes have been established in France, of which the Institut Pasteur (1888) and the Fondation Curie (1912) are the most famous. The former, comprising more than 35 laboratories, has seen the development of similar organizations throughout the world. The latter, generally known as the Institute of Radium, conducts research on the physiology and therapeutic applications of X-rays in the treatment of cancer, on general physics, radioactivity, and radiophysiology.

The Institut de Biologie-chimique (1938) conducts research in its application to French industry and agriculture, particularly in the physicochemical sciences.

The Institut Océanographique studies marine life. The Institut Alfred Fournier is concerned with venereal diseases. The Fondation Salgues engages in investigations in the biological sciences. The Institut Marey is an association for the study of methods employed in physiology. The Institut d'Optique is interested in the development of the science and industry of optics.

Learned and Technical Societies

There are upwards of 36 societies of national scope in France, of which 7 are of a general nature and the remainder devoted to the fields of agriculture, anthropology, astronomy and meteorology, biology, botany and horticulture, chemistry, entomology, geography, geology, mathematics, medicine, physics, and several of the natural sciences. The great academies are directly supervised by the State under appropriate ministries. In addition there are many regional societies and local bodies attached to the universities.

The number of technical societies in France is large. In chemistry, Société de Chimie industrielle and Société de Chimie de France are the most prominent, as is Société française de physique in the field of physics, Société française des électriciens in electricity, Société de biologie in biology, and Société de Chimie biologique in biochemistry.

Industry

Compared with other major industrial nations French industry, with the exception of a few outstanding firms, lags seriously in ability to apply results of research to practice. Industry in general maintains a passive attitude toward improvements in products so long as purchasers are satisfied. The French chemical industry, since 1918, has undertaken little commercial development of processes or products originated in French research laboratories—whether Government or privately owned. Except in distillation equipment, French engineers have made few contributions to modern chemical equipment.

The French people are not development minded. Secrecy prevails to a high degree both in established industries and in new developments. Many industries hand down secret processes from father to son. A common practice is use of private documents describing individual researches or inventions, which are placed in depositories for future use, particularly in the event of patent applications by others. Continental Europeans, particularly the French, tend to speak of research problems finished in the laboratory as commercially complete. French industrialists are reluctant to go through the pilot plant stage of development, preferring often to buy a completely developed new process with a performance guarantee.

The purchase of "manufacturing rights" to processes developed abroad has been a feature of French operations but has not been particularly beneficial to industry because the "rights" covered production for consumption in France only—not export. Such processes have not undergone further development but have tended to remain in their state of original installation.

Industrial research and science in the universities are much less closely coordinated in France than in Germany or Great Britain. In recent years lack of funds for research has aggravated the situation. Labor troubles with which industry has had to contend have either limited the funds available for research or when available, have made executives reluctant to spend them for this purpose.

In nearly every branch of French industry at least one outstanding research man may be found. In many industries, and particularly the chemical industry, technical direction is frequently by Swiss or Alsatians, the principal reason for which seems to be that university research training in France does not meet the requirements of industry.

The number of industrial research laboratories in France is comparatively small. Établissement Kuhlmann, largest of the chemical companies, maintains the most extensive in that field and is active in research on dyes, organic chemicals, and heavy chemicals. Cie. Gobain conducts research in its line of products—glass, heavy chemicals, and petroleum. Cie. Gaumont, one of the largest moving-picture companies in Europe, also manufactures starting and ignition systems, cameras and moving-picture apparatus, field glasses, and precision specialties, and maintains one of the largest staffs in Europe for research in these fields. The Thomson-Houston Company maintains a large central research laboratory for its activities in electrical machinery and supplies. Société Chimiques de la Grand Paroisse has been investigating the production and hydrogenation of shale oil. Other industrial concerns which have been active in research include Société Anonyme pour l'Étude et Exploitation des Procédés Georges Claude; Société Anonyme des Établissements Roure Bertrand Fils et Justin duPont; Société d'Éclairage, Chauffage et Force matrice; Société d'Électro-Chimie, d'Électro-Metallurgie et des Aciéries (Savoie); Société d'Électro-Chimie, d'Électro-Metallurgie et des Aciéries (Paris); Compagnie de Produits chimiques et electrometallurgiques, Alais, Forges et Camargue; Société anonyme des Matières colorantes et Produits chimiques de Saint-Denis; Société des Usines Chimiques Rhone-Poulenc; Comptoir des Textiles artificiels.

Noteworthy research accomplishments have been made by other industries such as alloys, metallic carbides, naval stores, and coal. Research on raw materials of the French colonial possessions, such as rubber, vegetable oils, phosphates, and agricultural products, has constituted an important sphere of activity.

French designers of packages for perfumes and cosmetics lead the world and have consciously or unconsciously exerted a world-wide influence on industrial design, not only in packaging but as well in architecture, furniture, equipment, automobiles, railroads, and other lines.

Although considerable research is conducted by trade associations, it has been difficult to ascertain its extent. The French rubber plantation interests maintain a research institute in cooperation with similar Dutch and British institutes for development of new uses for rubber. A foundry research bureau was organized in 1938.

Research in Germany

During the nineteenth century science in Germany made tremendous advances, and German scientists were encouraged to apply the results of their discoveries and inventions to the development of industry. The enormous growth which followed in the chemical, steel, electrical, and other industries was in large measure due also to the association of science with the traditions of German learning and the prestige which science gained from recognition by the Government. The Government and state research institutes, the universities and institutes of technology, and industry all played important parts in this remarkable development.

Germany was among the first countries to recognize the importance of research in science and industry before the World War, but perhaps the most brilliant period in her science occurred when a defeated nation turned to research as a means of overcoming the material and human losses sustained. Before the depression Germany was one of the leading nations in organized scientific research. With the ascendency of the Nazi regime a change took place in the attitude of the Government toward research, the efforts of which were directed to the interest of the national economy and preparedness.

Prior to 1933, the foundation of research and science in Germany was in the five states, each of which had its Department of Science and the Arts. The highest development was in Prussia. The state, through the Prussian Ministry for Science and the Arts, largely controlled important scientific and research personnel by such means as financial support of research fellowships, consultation fees, and guarantees for lectures.

Following the lessened ability of industry to bear its share of financing research and the consequent burden placed on the state in the post-war period, the character of German research changed, and the volume diminished somewhat by 1924. During the depression with its attendant unemployment, the proportion of scientific research done in institutes of technology, universities, state bureaus, and industry became high, and the trend of industrial research turned from new process developments toward improvements in old processes.

The attitude of National Socialist Germany toward research is indicated in the following preamble to the law of March 16, 1937, establishing a National Research Council (Reichsforschungsrat).

> The great undertakings which the Four-Year Plan has set for German science make it necessary that all the forces of research which can contribute to the fulfilling of these tasks be centrally coordinated and set in motion. The principle of free inquiry will not be interfered with by this direction of certain branches of science toward the goals of the Four-Year Plan, nor by the centralized allocation of research funds, nor by the systematic assignment of problems, since freedom of inquiry is based not on an arbitrary choice of problems, but on the independence with which the research process is carried out. At an historical moment like the present, when scientific investigation has the task of reaching goals on which the existence of the whole Nation depends, it is needless to explain why research must devote itself to this type of problem, and thus at the same time possibly have to neglect less important and less urgent problems—even when these latter may be more in keeping with the investigator's previous work and with the usual dispensation of funds.

The policy of giving a political coating to the scientific pill has been applied alike to Government, universities, research institutes and industry, to individual scientists, and to organized groups. The scientist has to demonstrate his usefulness to the nation.

Government Research Institutes

There are numerous research institutes in the various ministries, both of the Government and of the principal States. These cover a wide range of subjects from the physical and natural sciences to the social sciences and the humanities, and in numerous instances the work is supported in part by industry.

Among the most important of these are the Physikalische Technische Reichanstalt, leading research bureau of the State of Prussia, which is equivalent to our National Bureau of Standards. The Staatliches Material Prüfungsamt is the testing materials laboratory for Prussia. The Chemical Technical Institute is concerned with chemical and physical problems relating to general chemistry, explosives, metallurgy, and materials testing.

The German State Council for Research (1937) has as its object the coordination of scientific research, including activities of industrial research laboratories. One of its most important duties is furtherance of the Four-Year Plan. It cooperates with the Kaiser Wilhelm Institutes. Fourteen departments had been organized in 1937 as follows:

Physics, including mathematics, astronomy, and meteorology.
Chemistry and physical chemistry.

Power materials.
Organic industrial materials, artificial products, rubber, textiles, etc.
Nonferrous metals.
Geology, including mineralogy and geophysics.
Agriculture and general biology, including zoology and botany.
Forestry and timber research.
Military science and technics.
Electrotechnics.
Mining and smelting.
Iron and steel.
Medicine, including race research and race biology.
Military medicine.

The Government of Germany did not fully appreciate the importance of scientific and industrial research until in 1911 von Harnack, a disciple of von Humboldt, stimulated the interest and secured the financial backing of Kaiser Wilhelm II by pointing out that unless provision were made for research facilities Germany would lose its leadership in science and research. Thus was founded the Kaiser Wilhelm Society for the Advancement of Science. In 1937 it consisted of a group of 37 research institutes in the fields of physics, chemistry, biology, medicine, history, law, and the humanities. At that time the membership was about 675, and the number of investigators upward of 1,100. The various institutes have been started, fostered, and maintained by the Government and industry jointly and by private endowments, although most of the support has come from private industry and the Government. The endowments were entirely lost during the period of inflation, and the Government, being financially embarrassed, could not help them. Industry undertook 95 percent of the support of the various institutes. Again during the severe economic crisis beginning in 1929, some of the institutes experienced difficulty in continuing their research. The National Socialist Government granted the Society substantial and regular financial aid in return for which the Society promised loyal support to the new Government. According to the new statutes the President of the Society alone assumes all responsibility and is assisted by an Advisory Council. The newly elected Senate of the Society consists of representatives of science, industry, and Government.

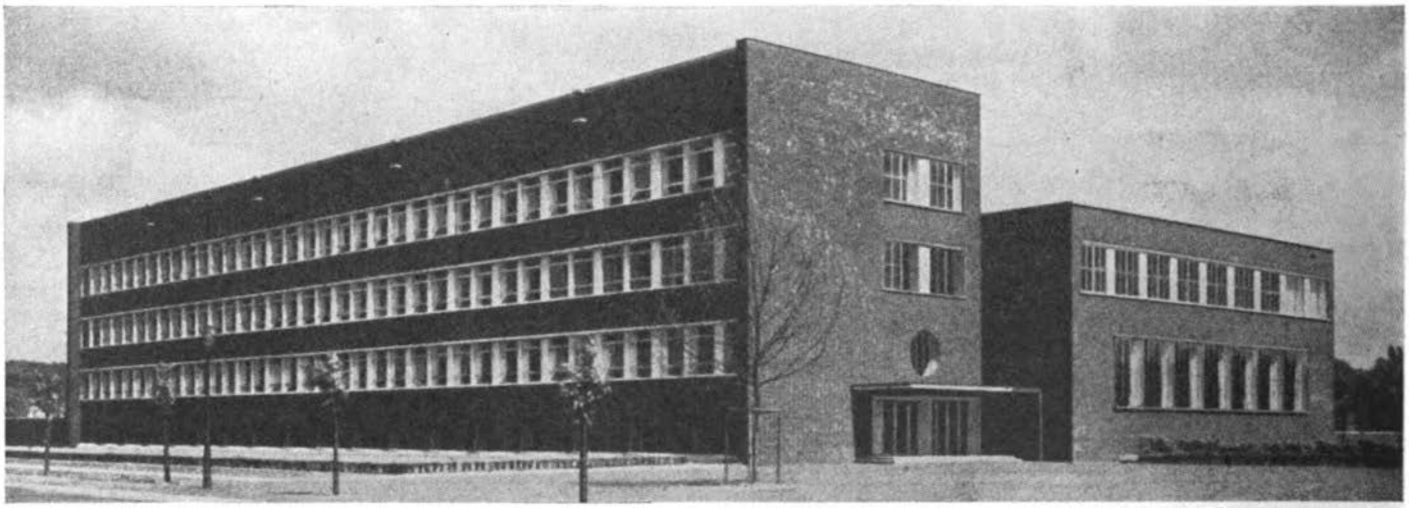
Under the National Socialist Party the Society has been described as "the general staff of German science in our peaceful campaign for the spiritual, cultural, and material development of our people." Recent reports of the Society have stated that its activities were widely increased for solution of problems related to the Four-Year Plan and that it enjoyed very generous Governmental support. It has been reported, however, that activities of some of the Kaiser Wilhelm Institutes have been curtailed since the outbreak of the war.

Universities

The remarkable industrial growth which Germany experienced up to 3 or 4 years ago was in large measure due to the fruits of the system of research in the universities and its coordination with industry. In scientific achievements and in benefits both to university and industry this plan excelled that of any other nation. It was stimulated by the ancient traditions and ideals of the universities which developed men of international fame in many fields.

The backbone of fundamental research in these universities was the industry sponsored system of postdoctorate research assistants to professors, who sometimes directed the work of as many as 20 or 30 men. Their number had been reduced by two thirds by the spring of 1939, with losses still mounting in the following summer.

Owing to the unemployment situation in Germany up to about 1935 the universities were crowded with



Photo, Stahl und Eise

FIGURE 57.—Kaiser Wilhelm Institute for Iron and Steel Research, Düsseldorf, Germany

students and it appeared that German industry would not be able to absorb all of the graduates. At that time there was serious talk of reducing the number of students enrolled by selective examination. As the self-sufficiency program developed, unemployment was practically eliminated and the demand for technical men absorbed all the unemployed with a resulting shortage in technicians. The 3 years of combined military and work service required of all young men, together with the rather unattractive economic standing of university graduates, tended to decrease the number of students in universities, thus aggravating the shortage of technically trained men. Race purges and discouragement over the future outlook in the academic field also contributed to this shortage.

Student enrollment in nearly all university courses decreased in 1936–37 to 57.8 percent of the 1932–33 figures. Those in engineering sciences dropped from 14,477 to 5,188 students, and in mathematics and natural sciences from 12,591 to 4,616 students. The decrease in the number of students has continued and with the outbreak of war some of the universities closed or courses were eliminated. The university courses, including those in technical subjects, have largely been reduced from 4 to 2 years.

The research strength of universities has been weakened in other ways. Heads of universities, if not members of the National Socialist Party, have been replaced for the most part by members appointed largely to prevent subversive activities. As faculty chairs have become vacant for normal causes or other reasons, they have been filled with men chosen primarily for their party records and secondarily for their professional qualifications. A generation may be required to restore these faculties to their former high planes. Capable assistant professors have become discouraged at not being advanced to these posts. Students have engaged in party activities with the result that studies became of secondary interest. Since the outbreak of the war the Government has brought pressure to bear on universities as well as industry to confine research to problems concerned with national defense.

Illustrative of the shift of university research from one fundamental field of endeavor to another in coordination with the progress of industry is the change of work from dyes to biological chemistry. Prior to 1914 a very large part of the research on dyes was carried on in the universities under the sponsorship of industry. After the war the dye industry increased at such an amazing rate that manufacturers had to take over most of the research. University research workers turned their efforts to biological chemistry, thus starting Germany's remarkable era of development in such fields as vitamins, hormones, pharmaceuticals, and tanning materials. This situation was comparable to that existing in dyes before 1914. Industry may eventually take over research in biological chemistry, as it did in dyes.

Industry

Germany has a framework for industrial research unequalled except in the United States and up to 1939 its research organization was developing more rapidly than ever. Most of the large manufacturing industries, particularly metals and chemicals, have been backed by strong, well integrated research staffs which were frequently larger for a given production than those in the United States. Characteristic of German industry, especially in chemicals, have been the large number of small and moderate sized companies employing up to 50 research workers. In recent years there has been a very marked trend away from the so-called "closeted" research, more especially with the larger companies, but not to the extent to which it has been carried in the United States.

The present regime appears to recognize the importance of well organized industrial research, the efforts of which are being directed toward self-sufficiency and preparedness. In some research, including that concerned with electric communications, biological chemistry, and certain types of alloys, Germany excels the rest of Europe, but is second to the United States in most if not all of these fields. More people were engaged about 1937 in laboratories for electrical communication development and research in Germany than in the United States, almost wholly on specific developments and designs immediately required. The development of tools of research, in which Germany was preeminent, is continuing, as witness outstanding work in X-rays, electronic diffraction, optical instruments, and other fields. Its engineers are equal to the best in applying the results of research to practice, although mechanization of industry is reported to be less developed than in the United States.

Recent years have witnessed a pronounced decline in the number of patents under the new regime, and foreigners have experienced increasing difficulty in securing patent protection.

In the past decade Germany has tended to license concerns in other countries for the utilization of new processes and manufacture of new products. These licenses are only given on processes or products on which an export trade could not be reasonably developed. This trend is due to the fact that since the war of 1914–18 German export potentialities have been reduced because of the well developed industries in former export fields. Tariffs or embargoes in these countries have made the export of chemicals, with the exception of specialties, almost impossible. To obtain foreign exchange the only recourse was to license processes. A number of German manufacturers maintained representatives in other countries for negotiating such licenses. Conversely, manufacturers in Germany have been granted licenses to use processes developed in the United States and other countries. Usually these licenses include technical assistance in getting processes into commercial production. Recent examples of licensing between Germany and the United States are those involving production of Buna rubber in this country and of nylon in Germany. Exchange of technical information between the United States and Germany in this manner and other ways has materially aided technological development in both countries.

The largest industrial research organization in Germany is that of the Interessen Gemeinschaft Farbenindustrie I. G., commonly known as the German I. G. Originally, this organization was a consolidation of well integrated competing plants each with well organized and complete research facilities. Centralization of research facilities was extremely difficult but has made great progress in recent years. While not entirely limited in scope of research, the large laboratories of the I. G. have been placing their main emphasis on problems related to plant activities. In cases of conflicting interests, problems have been frequently assigned to or divided among the laboratories best suited to handle the work. A definite proportion of fundamental research has been carried out in all the laboratories. It is of interest to note that at the Oppau laboratory 300 chemists were said to be working at one time on development of catalysts for high pressure synthesis. These laboratories may be roughly classified as follows:

Leverkusen—vat dyes, rubber chemicals and buna service, inorganic chemistry.
Ludwigshafen—Azo dyes, plastics and synthetic rubber.
Elberfeld and Hoechst—pharmaceuticals.
Wolfen—Bitterfeld—cellulose, rayon, synthetic fibers and photography, aluminum and metals.
Oppau and Merzeberg—nitrogen, carbon monoxide and hydrogenation of coal (high pressure).

The I. G. Farbenindustrie has lost many of its key research men in recent years, partly because of the necessity of transferring technical men to manufacturing, partly because of race purges, and for other reasons. In some instances replacements have been as high as five young graduates for each experienced research man. In other instances the post-doctorate

Photo, Chemnyco, Incorporated

FIGURE 58.—Laboratory of the German Interessen Gesellschaft Farbenindustrie

assistants of professors have been called in, to the detriment of research in universities. In recent years an unusually large number of outstanding research men reached the age limit and have been retired. To maintain continuity in research traditions and to profit from their experience these men have been retained as consultants and in many cases deliver lectures on their research experiences to the younger personnel. The experience of the I. G. is believed to be typical of many other firms maintaining large research staffs.

German research in electric communications, particularly in television, surpasses both in volume and quality that of any other European country. Some of the work is done in Government laboratories, such as that of the Reichspost, in telephony, radio, and television; some in Kaiser Wilhelm Institutes, as on magnetic alloys, magnetic measurements, and metallurgy; and a very important part by industry itself. The Siemens-Halske and Siemens-Schuchert combine, one of the largest electrical manufacturers in the world, does much research in electric communications other than wireless, telephony, and electric power. In 1937 this organization was credited with a staff of 2,000 scientists. The Allgemeine Electrizitäts Gesellschaft (German General Electric Company) engages in research principally on electric power. In 1939 Telefunken Gesellschaft and Fernseh (Bosch and Zeiss-Ikon interests) were doing 90 percent of the research in television, with research personnel larger than that of any other country.

Other great research laboratories are in the iron and steel industry (Krupp, Rochling Iron and Steel Works, Vereinigte Stahlwerke); glass (Schott and Genossen, Osram); nonferrous metals (Metall Bank A. G.); coal (Ruhr Chemical and others); photography (Zeiss-Ikon); textiles; shipbuilding (Deutsche Werke); electric insulation (Hermsdorf-Schomberg); potash (several potash producers and a trade association); inorganic chemicals (Goldschmidt laboratories); general chemicals (Degusa-Hiag); fine chemicals (Chemische-Pharmazeutische, J. D. Riedel-E. de Haen); synthetic camphor and menthol (Schering-Kahlbaum).

Many trade associations in Germany maintain extensive research laboratories, of which those in the coal, potash, cement, textiles, porcelain, varnish, and paint industries, among others, are doing the most outstanding work. In contrast to the American practice of organization of trade associations by the industries themselves, trade associations in Germany are organized by and under the control of the Government.

A comparison of research in the German coal industry with that of the United States reveals the sharp contrast in conditions which motivate research in a given industry. In the United States the coal industry, not having prospered relative to other industries, is little able to engage in extensive research. In this country coking of coal is done principally by steel and gas companies, whereas in Germany the coal industry itself engages in this operation. Research by coal interests here has been directed primarily towards stokers for the utilization of coal as is, while in Germany and England efforts have been toward utilization of the higher value products of coal carbonization with such developments as low temperature carbonization, utilization of the new types of tar therefrom, synthetic motor fuel, and chemical utilization of byproducts. Research of this nature in the United States is conducted mainly by the steel companies and the tar distillers.

In recent years a shortage of research workers, especially in fundamental lines, has arisen in Germany, not only from causes previously mentioned but as well from the smaller number of university graduates and the greatly stimulated tempo of industry. These conditions, together with the trend in universities from fundamental to applied research objectives, hold dim prospects of being alleviated and are causing industry concern about the future supply of fundamental research workers. Industry's desire to place emphasis on fundamentals so as to provide a training ground for future personnel is hindered by reason of Government demands for research promising immediate results. Should normal conditions again obtain, a long period will be required to train a new generation of research workers to the high order of experience and ability which characterized pre-Hitler Germany, thus rendering post-war recovery more difficult. Yet this shortage of research workers should not be taken to mean that industrial research in Germany has deteriorated, although some observers are of the opinion that it has become more superficial with the change of emphasis under the dictates of political exigencies.

Germany's plan for self-sufficiency necessarily brings upon herself the tremendous disadvantages to be expected from an economy based on internal rather than international considerations. In development of substitute materials and products from domestic resources so as to reduce the volume of imports to a minimum, it is obvious that the extra demands on Germany's raw material, labor, and energy resources, not to speak of its research resources, are huge. There must be more labor to produce the extra products of the mines, the fields, and the forests, more equipment to move and to process them, in turn requiring more labor, more chemicals, more energy, and so on almost ad infinitum. Shortages exist all along the line. The problems of applied research workers are thus multiplied manyfold.

Before permission to build new plants is granted, projects must first be demonstrated as in the interests of self-sufficiency or national defense. Then permits must be obtained for necessary building materials, equipment, raw materials, and labor. Delays in delivery of equipment are common. The time required to complete new projects is said to be about twice the normal. The very insistance upon use of domestic raw materials has delayed completion of some projects by several years because of the necessity of research on the use of prescribed materials. An example of such delay is production of the cobalt catalyst required for the Fischer-Tropf coal hydrogenation process.

Scientific and Technical Societies and Publications

A statement on research in Germany should not omit mention of the important role which her scientific societies and publications have played in the dissemination of scientific and technical information. The societies have assisted materially in dissipating the secrecy which formerly surrounded so much of German research. The leading chemical society, Deutsche Chemische Gesellschaft, is comparable to our own American Chemical Society. The meetings of local organizations of regional universities and institutes of technology have served a very useful purpose. These semiannual meetings of young men in university faculties (Privat Dozenten Sitzungen) afford opportunities for the younger researchers to present papers covering their work to their colleagues and heads of departments. The discussions serve to stimulate and guide the men in further research. The meetings serve as recruiting grounds for the advancement of worthwhile men. Such a plan might well be considered for adoption in the United States.

The symposium plan by which a few leading scientists or technologists are invited to address gatherings, and at which discussion and interchange of ideas are freely engaged in, has been successful in Germany and to some extent in England and other European countries. By this means university and industrial researchers in both fundamental and applied fields are brought more intimately into contact than is possible, for example, at the large meetings of some of the professional and technical societies in the United States.

Photo, German Library of Information

FIGURE 59.—Bacteriological Analyses by Students, Institute of Research, Berlin, Germany

A beginning towards the symposium plan has been made in this country.

In most of the sciences Germany has publications of world-wide reputation. Its Chemisches Zentralblatt, abstract periodical for chemistry and related sciences, can be compared only with our own Chemical Abstracts and the British Chemical Abstracts.

Research in Great Britain

Industrial research in Great Britain differs from that in most important industrial nations in several respects—some favorable and some unfavorable by comparison. The outstanding feature in Great Britain is the active Government participation in and subsidy of research through the trade association system, the special boards and committees representing numerous industries, and the Government's own research laboratories. Less obvious are the contributions which British scientists in applied fields have made through systematic publication of critical surveys of technical knowledge.

British industry has been slow in recognizing the importance of industrial research, but the First World War caused significant advances to be made in the application of science to industry. Research in universities has overcome to a considerable extent the stigma which once attached to work in applied fields. Lack of social and employer recognition of the professional status of research workers in industry has likewise been overcome to a marked degree. The former absence of cooperation between universities and industries has been replaced by a growing frequency with which professors serve as consultants to industry and by industry's grants to universities for fellowships.

Government research in science is directed mainly by three bodies which are directly responsible to Committees of the Department of Scientific and Industrial Research (1915), the Medical Research Council (1920), and the Agricultural Research Council (1931). The Royal Society also assists in making the research resources of the nation available to the Government. The University Grants Committee of the Treasury makes large grants to universities, the research activities of which share in the benefits.

Several of the Dominions maintain research organizations similar to those in England, cooperation with which is afforded through the executive council of the Imperial Agricultural College (1929) which is composed

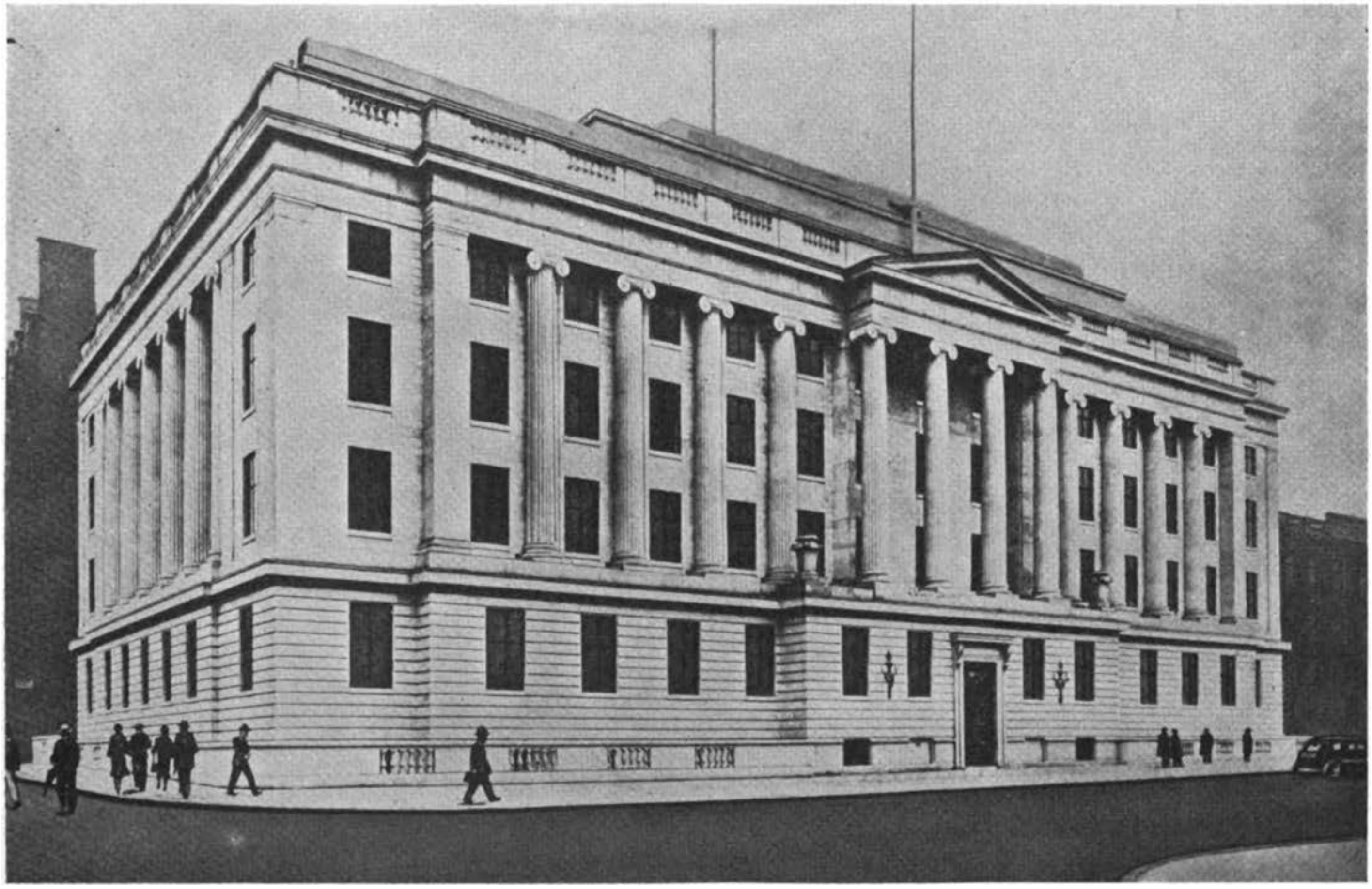


FIGURE 60.—The Wellcome Research Institution, London, England

of nominees of the United Kingdom, the Dominions and India, and the Colonial Office. This executive council administers several bureaus which act as clearing houses of research information.

Department of Scientific and Industrial Research

> The Department of Scientific and Industrial Research . . . was the outcome of a widely felt need for action to remove the defects in . . . industrial organization revealed at the outbreak of the Great War. The object of the Government was stated to be "to establish a permanent organization for the promotion of scientific and industrial research" throughout the United Kingdom . . . in peace, even more than in war—though for the time being the claims of the defence were paramount.[1]

The directing agency of the Department is an advisory council, but actual supervision is by special boards or committees. The functions of the council are to institute specific researches to establish special institutions, to study problems in particular industries or trades, and to administer research studentships and fellowships for recruiting scientific and technical professions. The expenditure of the Department in 1937–38 was £872,127 gross or £637,200 net. Total receipts in that year amounted to £234,927, of which fees for paid work were £80,486, contributions to cooperative research £17,966, payments by other Government Departments for services rendered £81,923, and the remainder from miscellaneous sources.

The Department maintains 8 special research establishments and some 30 boards or committees, and cooperates with some 20 industrial research associations, the Medical Research Council and the Agricultural Research Council. About 20 Government agencies have liaison representatives in the Department.

The special research establishments are:

- National Physical Laboratory, Teddington.
- Geological Survey and Museum, London.
- Fuel Research Station, Greenwich.
- Low Temperature Research Station, Watford.
- Forest Products Research Station, Princes Risborough.
- Chemical Research Laboratory, Teddington.
- Radio Research Station, Slough.

The boards and committees are:

- Building (Materials and Construction) Research Board.
- Committee on Testing Work for the Building Industry.
- Chemistry Research Board.
- Food Investigation Board.
- Committee of Management, Low Temperature Station for Research in Biochemistry and Physics, Cambridge.
- Metallurgy Research Board.
- Road (Materials and Construction) Research Board.
- Water Pollution Research Board.
- Atmospheric Pollution Research Board.
- Dental Investigation Committee.
- Gas Cylinders and Containers Committee.
- Illumination Research Committee.
- Lubrication Research Committee.
- Road Tar Research Committee.
- Steel Structure Research Committee.
- Committee on the application of X-ray Methods to Industrial Research.

The trade associations are:

- The British Cast Iron Research Association.
- The British Iron and Steel Federation (Iron and Steel Industrial Research Council).
- The British Refractories Research Association.
- The British Electrical and Allied Industries Research Association.
- The British Scientific Instrument Research Association.
- The British Association of British Paint, Colour, and Varnish Manufacturers.
- The Institution of Automobile Engineers Research and Standardization Committee.
- The British Cotton Industry Research Association.
- The Wool Industries Research Association.
- The Linen Industry Research Association.
- The British Launderers' Research Association.

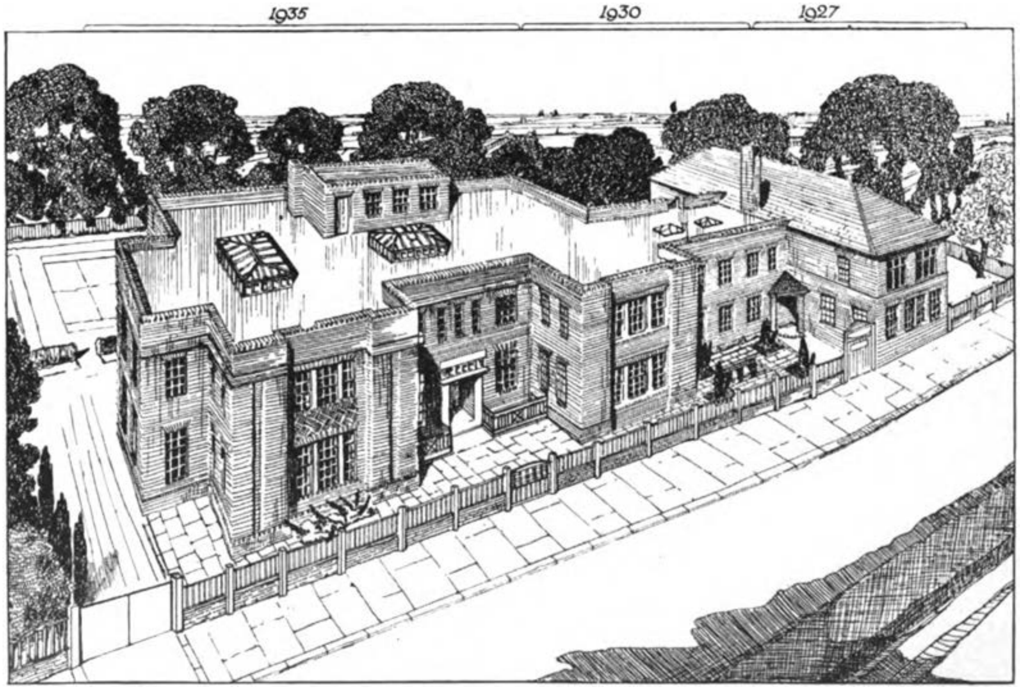


FIGURE 61.—The Paint Research Station, Teddington, England

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[1] Heath, Sir Frank. Government and scientific research. London and the advancement of science. London, British Association for the Advancement of Science, 1931, ch. 5, pp. 205–206.

The British Leather Manufacturers' Research Association.
The British Boot, Shoe and Allied Trades' Research Association.
The Research Association of British Rubber Manufacturers.
The British Association of British Flour Millers.
The British Association of Research for the Cocoa, Chocolate, Sugar, Confectionery, and Jam Trades.
The British Food Manufacturers' Research Association.
The Printing and Allied Trades Research Association.
The British Colliery Owners' Research Association.
The British Non-Ferrous Metals Research Association.
The British Coal Utilization Research Association.
The British Pottery Research Association.

A few trade associations have conducted research without benefit of Government subsidy and have made important contributions to the advancement of their industries. Among such organizations are:

The International Tin Research and Development Council.
The Gas Research Board (sponsored by the Institution of Gas Engineers and the British Gas Federation).
The Shellac Research Bureau.
Associated Portland Cement Manufacturers, Ltd.
Institute of Brewing.

The Government research laboratories have many notable accomplishments to their credit. While they have lagged somewhat behind in industrial research, the application of their results to industry will probably be further extended.

The National Physical Laboratory performs both research and development work. It plays an important part in cooperation with the Department of Scientific and Industrial Research, which supports a considerable volume of the research activities. Its aerodynamics laboratory, supported almost entirely by the Air Ministry, is the most important center of aviation research in the British Empire and is engaged in much war work. The laboratory is understood to be doing considerable research for other departments of defense. Its gross expenditures in 1937–38 were £252,209, and receipts £141,302.

The work of the Fuel Research Board corresponds closely in many respects to that of the Coal Division of the United States Bureau of Mines, its main object being the application of science for better utilization of British coal resources. Its gross expenditures in 1937–38 were £103,240 and receipts, £8,458. The Chemical Research Laboratory has numerous achievements to its credit, a recent interesting one being the application of certain forms of synthetic resins to purification of water.

The trade association plan of cooperative research has not been free from certain disadvantages and criticisms.

> The principal difficulty has been the equitable distribution of the results. The larger companies equipped with laboratories apply the results of fundamental investigations and gain a commercial advantage. It has been a problem to devise a plan by which the smaller concerns can participate in the results of cooperative research for which they have paid their proportionate share. One solution has been to encourage the small concern to use the laboratory as a school for foremen in the study of new processes.[2]

Sir Frank Heath, former secretary of the Department of Scientific and Industrial Research, has pointed out other difficulties in the system. Firms have failed to use discoveries. A discovery made by one research body may be useful to another industry, yet be neglected. New devices have been "still-born," either because plant and staff necessary to translate them to commercial practice were lacking or because funds were unavailable.

Instances of the inability of certain industries in need of research but unable to raise the minimum of £5,000 per year necessary to receive Government support have been numerous. The plastics industry has secured what service it can from the Chemical Research Laboratory at Teddington. For the same reason research on hard fibers has been combined with that on linen, and that on silk with research on cotton. The rayon industry formerly had its own laboratory, but transferred its work to the cotton laboratory.

The necessity for meeting the £5,000 annual quota has compelled some of the association laboratories to devote most of their time to routine testing and trouble shooting in order to keep the industries sold on the value of the work, and some research carried out in these laboratories has been done almost surreptitiously.

> It is obvious from a review of the work undertaken, that the Department (of Scientific and Industrial Research) furnishes research personnel and facilities for the work of industries and associations having an insufficient volume to justify separate organizations of their own.[3]
>
> When the British Government, after the war, began the creation and maintenance of state-subsidized research laboratories for certain industries, it cannot truthfully be said that industry in general in England was research conscious.[4]

This situation has undergone great change, especially in recent years, according to numerous authorities. In 1937 it was said that "industry in England is 'research minded' and apparently feels that the future prosperity of their own companies and the nation depends upon the results of research."[5] In the same year it was reported that the keynote of organized research in England was—

> Speed-up and extension of industrial research in the national program . . . particularly the scientific refinement of existing

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[2] Holland, Maurice. Research in Europe. A comparative study of the national and industrial organization. Presented before the Division of Engineering and Industrial Research of the National Research Council, November 11, 1924.

[3] Harris, R. C. European laboratory tour impressions. What we found behind the scenes in European research, 1937.

[4] Alexander, E. R. Research consciousness among leading industrial nations. Broadcast over Station WABC August 12, 1937.

[5] See footnote 3.

processes and technology and the fullest utilization of the natural resources and advantages which it now possesses.[6]

Bernal [7] states that it has been extremely difficult to raise money for cooperative research by trade associations, giving as reasons that the chief competitive value of research is lost if carried out cooperatively, and the lack of appreciation of scientific research in any form. Nearly all the reports of the Department of Scientific and Industiral Research have shown difficulties in persuading industries to take up research. Much of English industry consists of small factories, employing from 20 to 100 men. Most of these firms do not have the resources to undertake research and many have difficulty in maintaining useful contacts with national research projects through their trade associations. Furthermore, the Government has been reluctant for political as well as economic reasons to take active part in the application of science. It cannot exploit or sell the results of its research except in war emergency.

The Fighting Forces

Prior to 1914–18 there were no systematized efforts to study the service which science could render to the national defense. After the outbreak of the war of 1914–18, technical research in the fighting services, except for that carried on secretly in military establishments, was conducted in cooperation with the Department of Scientific and Industrial Research. Coordination was through the directors of scientific research from the Admiralty and the Air Ministry, and from the War Office by various boards and committees. Medical research, however, came under the medical directors general of the three fighting services, and was in close cooperation with the Medical Research Board. The three fighting services jointly maintain the Research Department at Woolwich for research on explosives, metallurgy, and radiology. In addition each service has one or more specialized research establishments, and uses facilities of industrial concerns. At Porton Field research in chemical warfare has been particularly important.

During the present war and until the surrender of France, liaison between the Advisory Council on Scientific Research and Technical Development was effected through the Mission scientifique franco-brittanique which was in contact with the entire French wartime scientific organization. A direct link was also established between the Ministry of Supply and the French Ministere de l'Armement, the facilities of which were available to the Advisory Council on matters relating to scientific invention through an officer of the Ministry of Supply located in Paris.

An advisory research council has been formed by the Council of the Chemical Society, the principal purpose of which is, when approached, to call to the attention of specialists research projects which may be of aid to the nation during the war.

Universities

Research in universities in England is principally fundamental in character. Until a few years ago academic research was more desirable from a social standpoint than industrial research, so much so that industrial laboratories were unable to recruit men of the highest abilities in graduate work at the universities. This condition has improved greatly in recent years, however, and in fundamental fields has become less surrounded by secrecy and restraint. It was also formerly considered in bad taste for the academic researcher to let his findings be applied in industry, but in the early part of the last decade professors in universities began to cooperate with industry by serving as consultants. Imperial Chemical Industries, Ltd., was instrumental in starting this movement, which has proceeded with increasing momentum up to the present. These university research workers have performed excellent services, at the same time maintaining their social standings. Some changes were made in the curricula of technical courses to meet requirements of industry, and some universities initiated courses in chemical engineering. Chemical engineers heretofore had been self-made—often mechanical engineers associated with chemical enterprises. Closer cooperation between universities and industries has also been fostered by the establishment of fellowships and the donation of research grants to professors by industries to assist in purchasing materials and equipment.

With some exceptions university laboratories have operated under the disadvantages of small size, inadequate equipment, and interference of teaching with research. The large grants made to some university laboratories for fundamental research have been extremely helpful in remedying these conditions. There has been no organized direction of research in universities. British university scientists are rendering yeoman service for the national defense, notably in military gases.

A number of British universities have been active in applied research, among which should be mentioned Cambridge, Oxford, and London for their work in chemistry, Leeds in textiles, Birmingham in fuels, and Sheffield in iron, steel, and ferrous alloys. The

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[6] Holland, Maurice. High-spot impressions of significant trends in research in England, France, Germany. What we found behind the scenes in European research, 1937.

[7] Bernal, J. D. The social function of science. London, G. Routledge and Sons, Ltd., 1939.

universities of Edinburgh and Glasgow have likewise been doing considerable applied research.

Industry

The development of industrial research owes much to the professional attention accorded in England to the cultivation of knowledge in a systematic manner. This began in an important way toward the close of the nineteenth century, but in special fields had its beginnings earlier. Engineering as we know it had its birth in England about 1750. Since that time, and especially in the last 50 years, applied science has been cultivated to a constantly increasing extent. The British were leaders in industrial development prior to the research era in industry. Chemical engineering, as it concerned the design, erection, and operation of plants in chemical and related industries, had its birth in England, the concept of unit operations having come later in the United States. Professional recognition came to be enhanced by publication of critical surveys of technical knowledge, of which prominent examples have been Guttmann's work on explosives, Sir Boverton Redwood's masterpiece on petroleum, Cross and Bevan's classic on cellulose, and Lewkowitsch's compilation on oils and fats. With one or two exceptions, however, including Imperial Chemical Industries, Ltd., England probably is still excelled by Germany in skill of translating results of applied research to commercial practice.

Results of research by British industry are generously published although not so openly and freely as in the United States. Research executives commonly attend technical meetings but their subordinates do not to the extent practised in this country.

Concurrent with the change in attitude toward applied research by universities a similar transformation occurred in industry, which placed more stress on research and endeavored to make up for lost time. The social disadvantages attaching to industrial research have been largely but not wholly removed since the First World War. The practice of purchasing processes and products developed abroad, however, still prevails and is a natural outlet for idle capital.

It is difficult to estimate the number of industrial research laboratories in England: Industrial Research Laboratories, prepared by the Association of Scientific Workers, is far from complete. Of 450 industrial firms conducting research, only 80 replied to inquiries. Many of the most prominent laboratories are omitted, among them those of British Distillers, Ltd., Anglo-Iranian Oil Company, Unilever, British Celanese, Courtalds, J. Lyons and Company, Buroughs-Wellcome, the Gas, Light, and Coke Company, South Metropolitan Gas Company, Mond Nickel Company, the British Aluminium Company, most of the laboratories of Imperial Chemical Industries (which had 18 research stations operating or authorized in 1938), and others.

Bernal[8] says, however, that four-fifths of industrial research, other than that carried on by the Government, is undertaken by no more than 10 large firms. He estimates the number of firms maintaining research laboratories as between 300 and 600, and the total money spent on industrial research as perhaps as much as £2,000,000 (exclusive of Government expenditures). It is possible, however, that routine testing is included in the research personnel.

The research organization of Imperial Chemical Industries, Ltd., is outstanding and has received many favorable comments. It has a technical development committee and an executive committee on development, which is tied up with a sales committee, to make decisions on research in progress. The ability of I. C. I.'s engineers to convert the results of research to practice has been outstanding.

Societies

The scientific, professional, and industrial societies represent influences tending to improve conditions surrounding research both in fundamental and applied fields. The opportunities afforded at their meetings for presentation of papers on new subjects and subsequent discussion thereof, personal contacts, and exchange of ideas, have assisted materially in dispelling the secrecy which formerly characterized much of the research especially in applied fields. In chemistry and chemical engineering the Society of Chemical Industry, the Institute of Chemists, and the Institution of Chemical Engineers have been particularly prominent and have done much to elevate these professions to positions of national importance. The symposium plan, developed to the highest degree in Germany, is perhaps next most advanced in England, the meetings of the Faraday Society being a particularly good example.

The Royal Society of London, founded in 1640, stands in close and important relationship to the Government by reason of the nominations which it has become a function of the society to make for scientific positions in the Government, and also because of the special research problems which it undertakes for the Government from time to time. The Royal Institution (1799) maintains a library and laboratories and promotes research in connection with the experimental sciences.

Research in Italy

As in other totalitarian states the national economy of Italy is directed toward self-sufficiency and preparedness. Italy is so lacking in material resources

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[8] See footnote 7.

and her population is so predominantly agricultural that her aims toward self-sufficiency have been realized only in relatively small degree. One of the principal directions which these efforts have taken is the manufacture of chemical and related products hitherto imported. Other major activities include motor fuel from agricultural materials, low-temperature distillation of lignite, new sources of cellulose, new fibers, and development of colonial resources. More recently development of metallic and nonmetallic minerals and certain coal deposits has been contemplated.

Mussolini and high-ranking officials are keenly aware of the importance of research in following this plan. The national economy program places emphasis on applied rather than fundamental research, as in Germany.

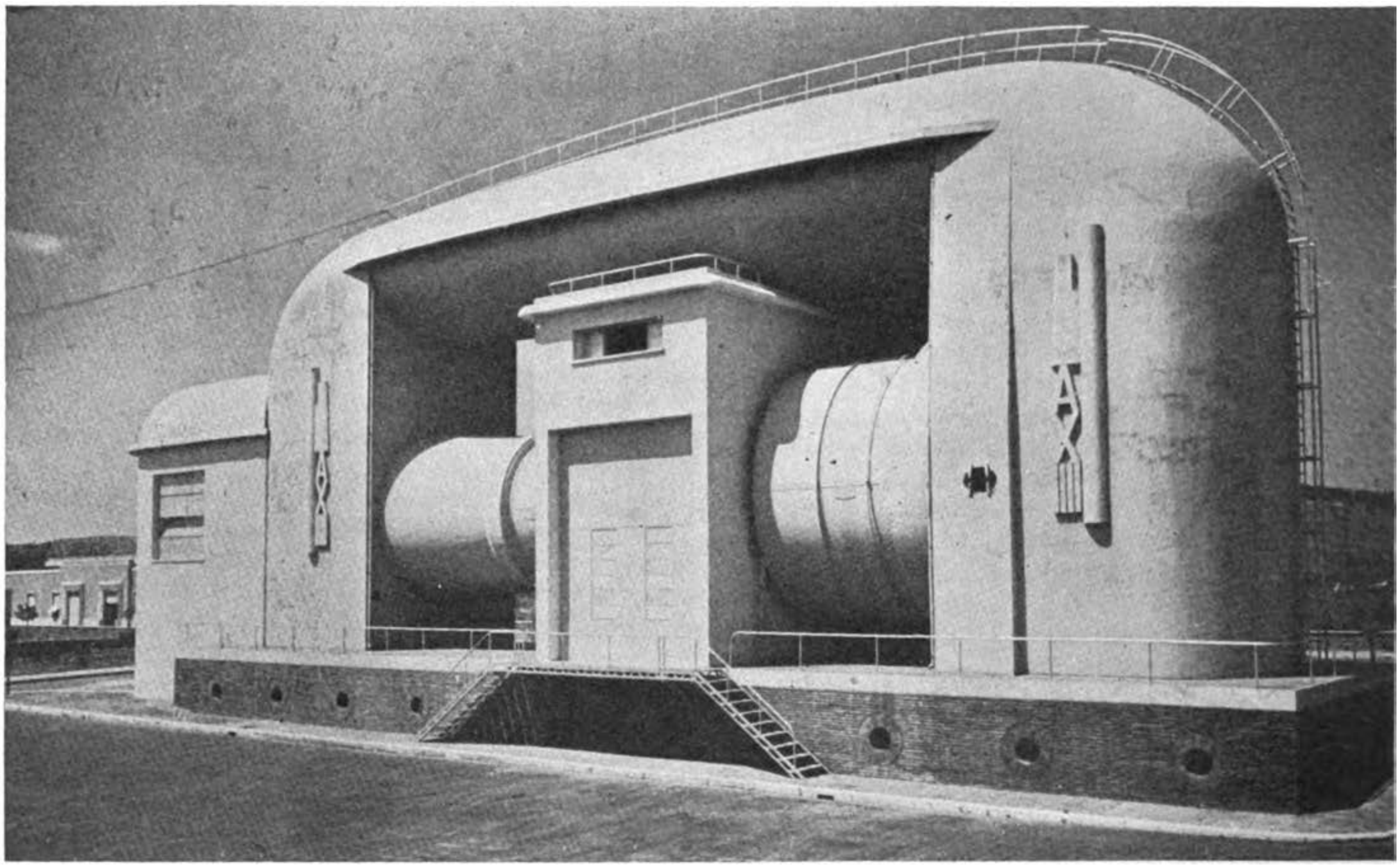
The National Research Council

The National Research Council of Italy was first set up in 1921, but with its peculiar organization was unable to yield the results expected of it. The National Government, recognizing the benefits which might accrue from such an institute, however, reorganized it about 1928. Under a better-defined legal status the council became a permanent consulting agency of the head of the Government and of the Ministry of Public Instruction for all problems concerning the development and progress of scientific activity at home and abroad.

The council is also charged with the control of scientific apparatus and biological and scientific products. Its approval is required of Government loans for plant expansion, new equipment, and capital accounts, in connection with which it gives technical advice and lends assistance through Government and university research. Representation of Italy at international scientific and technical meetings is controlled by the council.

The National Research Council is supported by funds appropriated by the Government, by the Ministries which call upon it for services, by industrial concerns which utilize its facilities, and by royalties from patents held by it.

The National Research Council is organized along lines similar to the council in the United States. The scientific and technical divisions correspond closely to our own. Committees are charged with specific research problems in such fields as industrial development, public health, engineering, and agriculture.



Hamilton Wright Photo

FIGURE 62.—High-Speed Wind Tunnel, Government Aviation Research Center, Guidonia, Italy

Its functions are manifold. It seeks to eliminate injurious industrial competition through research, equipment, and personnel. The monthly research programs of all industrial, university, and Government research laboratories, which are required by the State, are reviewed by the council for the elimination of unnecessary duplication and the assignment of specific problems to appropriate laboratories. It compiles and disseminates technical and scientific bibliographies so that the work of Italian scientists may become better known abroad, and studies means for development and application in Italy of inventions made in foreign lands.

Government

The Ministry of Corporations performs duties similar to but with authority extending far beyond those of our Departments of Commerce and Labor. Close cooperation is maintained with industry through individuals and committees on problems of production, labor relations, and improvements of processes and products.

The Pontifical Academy of Sciences

The Pontifical Academy of Sciences, an international organization, was organized in 1937. In its first year of existence an inquiry was instituted among members to determine what its most useful function would be. Replies indicated that the academy should not restrict its activities to publications of individual scientific communications but should take advantage of the freedom of action guaranteed by its scientific independence of race or creed to strengthen the bonds between the various sciences.

Universities

Research in Italian universities was formerly devoted principally to fundamental research and hence did not result in training men entirely suitable for industry. In recent years the industrial progress produced by the self-sufficiency program has caused the scientific and technical schools to concentrate their efforts on training men better qualified to meet the enlarged demands of the industries. This change has had a noticeable effect on the type of research being carried out at the universities, most of which is now in connection with industries.

The Government has given financial support to research in universities, five having received grants for industrial research in 1939. Examples of typical applied research in some universities are: At the Polytechnic Institute of Milan, a new process for production of water gas by the reaction of steam on oil gas, and utilization of lignites; at the Institute of Electrochemistry, investigation of the electrochemical recovery and extraction of copper, nickel, and tin; at the University of Milan, work on volcanic gas; at Turin University, a number of specific organic chemical projects; at Padua University, preparation of iron oxides and mineral colors; at the University of Naples, development of alpha cellulose from Italian raw materials; at the University of Rome, problems of high-pressure synthesis.

Publications and Societies

Excellent scientific and technical journals are published in Italy. In the chemical field Gazzetta Chimica Italiana and Giornale di Chimica Industriale ed Applicata, and in biology Giornale di Biologia Industriale, Agraria, ed Alimentare have presented many fine contributions. Likewise the scientific and technical societies, as for example the Italian Chemical Society and the Society of Applied Science, have made substantial contributions to the advancement of the several disciplines in both fundamental and applied fields.

Industry

The growth of nationalism in the development of the self-sufficiency program had as its goal the restriction of trade among the nations of Europe. The capacity for the manufacture of chemicals and other products required in Europe was more than sufficient to supply normal demands. Nationalism required that Italy, as well as other nations not normally industrial, develop complete chemical industries within their borders. This necessitated use of facilities, resources, and trained personnel for the development of the necessary techniques which were well established in other countries. In trying to accomplish in a short time the efficient results achieved by gradual development in other countries, processes were developed which were not always economically sound. In diverting trained personnel to this type of work very little real research in new fields has been carried out.

In 1934 an Italian professor estimated that there were about 60 industrial research laboratories in the northern Italian industrial area and 200 in the entire country. Like all projects for new manufacturing plants, new industrial research laboratories must be approved by the National Research Council.

The Montecantini Company, by far the largest chemical manufacturer in Italy, maintains one of the largest if not the largest research staff in the country. In accordance with Fascist policy of self-sufficiency, most of its research is in applied fields, and in the past decade the company has initiated production of many chemicals not previously produced in Italy. Recently the company allocated a sum of 20,000,000 lire for expansion of research facilities in a new center called the Instituto Scientifico per Ricerche e Sperimentazioni Chimiche. It is reported that the laboratory will be the most comprehensive in Italy.

One of the materials of which Italy has a serious shortage is cellulose. Much effort has been directed toward utilization of such cellulosic materials as straw, cornstalks, and esparto, and in the development of rayon including staple fiber and other fibers. Production of cellulose from straw has been successfully developed, but the extent to which it has relieved the shortage in cellulose is not indicated.

Italy has been a leader in Europe in development of rayon and new textile fibers. Chatillon S. A., Cisa, and Snia Viscosa have conducted research in rayon including admixture with other fibers. The latter company developed the woollike casein fiber Lanital, the virtues of which as a substitute or supplement for wool, both economically and in practical use, have yet to be fully demonstrated. Most of the requirements of casein for this new fiber are imported.

Società Boracifera di Larderello has achieved conspicuous success in the development of boron and iodine products and utilization of steam from volcanic fumaroles. Ufficio Tecnico Ammonia Casale, S. A., is noted for its development of the Casale process of nitrogen fixation. Film-Fabriche Riunite Prodotti is also active in research.

The Pirelli Rubber Company has been engaged in developing a process for manufacture of synthetic rubber of the Buna type, but as late as last summer no decision had been reached as to whether the German process based on acetylene from calcium carbide would be used, or the former German process now used by Russia employing ethyl alcohol as a raw material. It would be necessary to import the coal for manufacture of calcium carbide.

Among other industries which have been developed recently are aluminum, magnesium, cadmium, chemical pigments, dyes, varnishes, pharmaceuticals, electrochemicals, and photographic materials. Plans for cultivation of guayule to supplement requirements for latex have been pushed. Engineering developments in power, including use of natural steam of volcanic origin, and clearing of swamplands, such as the Pontine Marshes, where a model town has been built, have typified activities in other directions.

The Institute of Ceramics has been investigating the substitution of domestic for imported raw materials in the ceramics industry. The Scientific Institute of Industrial Research, Milan, has done research in various fields. A recent undertaking was the study of a new enzymic action on broom plant for production of fiber.

Research in the Netherlands

While the amount of industrial research in the Netherlands has been limited, from the standpoint of the size of the country, it has been outstanding both in amount and quality. The Phillips Laboratory at Eindhoven, engaged in activities similar to those of the General Electric Company, is one of the most outstanding in Europe as regards personnel and quality of work in electronics, radio, television, and related fields. Its laboratories are especially well designed for carrying out industrial-research programs. The Shell Company has noteworthy accomplishments to its credit in petroleum, and in the summer of 1939 was planning extensive additions to its laboratories in Amsterdam which were expected to make them among the largest petroleum-products research laboratories in the world. The States Mines, although Government owned, has done considerable research on coal, paid for from profits of the organization's commercial operations. Cooperative Superphosphate Works and Koning and Bienfait are also actively engaged in industrial research. The work of Kogl and of Jansen in biochemistry is particularly to be noted. Important work has been done on enamels and chrome leather.

As much of Netherlands' trade is dependent upon colonial materials, a considerable portion of the research activities is focused on these. Industrial and medical research in the Netherlands Indies has been notable. Netherlands has led the world in research on cocoa and chocolate and has made valuable contributions to knowledge of cinchona, rubber, and shellac.

Small companies not maintaining their own laboratories have procured research services by means of fellowships or by retaining as consultants university professors who have thus served two or three concerns and sometimes have been directors in them. Several companies have cooperated in the building or equipment of such laboratories.

The universities in the Netherlands have generally been well endowed and possessed potentialities for excellent research work, the outlook for which, however, has been said to be less favorable than 20 years ago because of the higher costs. The universities of Amsterdam, Delft, Groningen, and Leiden have been particularly active in research. The Van der Waals Laboratory at Amsterdam is noted for Prof. Michels' exceptional fundamental research involving very high pressures.

The Amsterdam Academy of Sciences is similar to our National Research Council, and there are many professional and scientific societies in the Netherlands.

Research in Scandinavian Countries

The industrial research of Norway and Sweden revolves largely around the utilization of their natural resources—iron ore, cellulose, arsenic, pyrites, hydroelectric power, and other less important materials—rather than in dissipation of efforts toward attaining self-sufficiency. These countries are more noted not only for their engineering skill but also for their recent accomplishments in basic research. Sweden produced Nobel, the inventor of dynamite, and de Laval, inventor of the centrifuge.

Svedberg, developer of the high-speed centrifuge, and his assistants at the University of Uppsala are doing the most outstanding work in the world on the centrifuge and its application in biological and chemical fields. The Academy of Science in Stockholm has constructed a modern and well-equipped physical-research institute. The laboratories are equipped with a fine cyclotron and one of the best ruling engines for diffraction gradings. Here is being conducted under Professor Seigbahn important physical research of a very high order, including X-ray and nuclear research.

Cellulose is a product which Norway, Sweden, and Finland each has in abundance, and each has been competing with the other on improvements in processes of recovery. Sweden has been conducting much research on utilization of lignin from pulp operations, but the results are said not to be encouraging. Some 20 mills producing alcohol from sulfite waste liquors, however, have benefited by research. Production of "tall" oil from sulfate pulp waste is mainly a Swedish development. Production of gasoline substitutes from wood has been under investigation there.

Sweden is famous for its iron-ore deposits and its steel. She has been conducting much research in this field, including alloys. The pyrites deposits of the country have yielded sufficient arsenic as a byproduct to exert a depressing influence on the world market for that product. Faced with legal restrictions on disposal of arsenical residues, Bolidens Mines has conducted intensive research on new outlets for arsenic and partially solved the problem by use of arsenic in preservation of wood poles and piles.

Industrial research laboratories which have been particularly active in Sweden include those of the Allmänna Svenska Elektriska AB. Västerås (electric equipment), Allmän Telefen AB. L. M. Ericsson (telephone equipment wires and cables, etc.), AB. Bofors (ordnance forgings and castings, tool steel), Bruks Koncerne AB and Stora Kopperbergs Bergslags AB, two of Sweden's leading iron works, Svenska Cementförsäljnings AB, an association of Swedish cement manufacturers, and Reymersholms Galma Industri (phosphates, heavy chemicals).

The Aga Company in Sweden has done applied research on a variety of equipment for household and commercial uses, such as stoves, refrigerators, and sweepers. An important activity of the Consumers' Cooperative Union in Sweden has been in applied research on products which it manufactures for use as rubber goods, vegetable oils, rayon, fertilizers, foodstuffs, and some heavy chemicals.

The Swedish Iron Masters' Association, composed of most of the Swedish mining companies, has done much valuable work for its members, and has assisted them both by loans and through cooperation with the Academy of Engineering Sciences.

A proposal has recently been made to the Swedish Riksdag for centralization and rationalization of scientific and industrial research. The central institute would become a foundation supported financially by both Government and industry, with the Academy of Engineering Sciences as the neutral party. Committees and institutes which would be parties to this plan are as follows:

Committee for the Study of Couplings in High-voltage Electric Wires and Cables.
Association for Rational Textile Washing.
Forest Scientific Committee.
Welding Committee.
Corrosion Board.
Gasgenerator Board.
Air-Conditioning Committee
Cool-Technical Committee.
Aeronautical Committee.
Shale Committee.
Committee for Domestic Motor Fuel.
Fuel-Technical Committee.
Swedish Iron Masters' Association.
Swedish Cement Association.
Steamheat Institute.
Charcoal Laboratory.
Cement Laboratory.
Technical X-ray Central.
Laboratory for Boilers.
Electroheat Institute.
Central Testing Institute.
Royal Building Board.

Norway had its Birkeland and Eyde, codevelopers of the arc process of nitrogen fixation. The enterprise and vision of these men, together with Norway's ample supplies of hydroelectric power have placed that country high in the world's nitrogen and electrochemical industries. To be sure the arc process for fixation has been replaced by synthetic ammonia, but Norsk-Hydro contributed a method of obtaining the soda of synthetic sodium nitrate from sea water. More recently comes news of this company's process for recovery of potash from the same source.

Industrial research in Norway has been more limited than in Sweden. Although the Aluminum Company of America and Union Carbide and Carbon Corporation each have plants in Norway these companies have conducted little or no research there other than on trouble shooting and plant problems.

Norway has been the largest producer of cod-liver oil in the world. The Norwegian canning industry has been conducting research for the fishing industries, and recently determined the vitamin D potency of different fish and fish products.

As Denmark is a small and predominantly agricultural country, the extent of research has been comparatively small. Nevertheless in some fields outstanding work has been done. Most notable perhaps has been the work at the laboratory of Professor Niels Bohr in Copenhagen on atomic structure and biophysics. P. A. Hansen's work in zymology at the Biotecknisko-Kemish Laboratory is world famous, as are S. P. L. Sørensen's researches in the same field and in hydrogen ion concentration at the Carlsberg Laboratory in Copenhagen. The University of Copenhagen and the Polytechnic Institute in Copenhagen have been doing splendid work in pure and applied science.

Research has advanced the Danish dairy industry to a high degree of excellence. Danish hydraulic engineers are credited with many notable accomplishments in their field. The chemical industry is small but research has accomplished useful ends in certain branches such as fertilizers. No research has been carried on in Denmark in the electrical communications field.

The Carlsberg Brewery was bequeathed by its founders to the support of scientific research and art. Annual revenue from the source devoted to science is 1,300,000 kroner, a substantial sum for a small country such as Denmark.

In general, support of industrial research by the governments of the Scandanavian countries has been unimportant but in recent years such aid has increased substantially. In Sweden, for example, State grants in aid of research as a whole did not average over 40,000 crowns annually up to 1935, but were increased to 500,000 crowns in the 1938–40 budget. In addition the Swedish Aeronautical Committee received an appropriation of 2,500,000 crowns for experimental work and the erection of laboratories and other buildings. The extent of cooperative effort has been one of the more prominent features of research in Scandanavia.

R. Schudel Photo

FIGURE 63.—Jungfrau Institute for Scientific Research, The Jungfrau, Switzerland

Research in Switzerland

Industry in Switzerland, being almost wholly dependent on imports for its raw materials, has been able to compete in international trade by concentrating on the superior quality of its products, and on certain specialties. Foremost among its industries are watches, dyes and pharmaceuticals, perfumes, electrochemical products, certain textiles, machinery, and foods. In recent years, and particularly under the strained international relations which have prevailed, considerable efforts have been devoted to make the country less dependent on imports of certain intermediate and finished products, as for example, alloy steel for watch springs, and high-temperature glass for use in X-ray tubes, electronic devices, and high-energy incandescent lamps. This nation has been a leader in research in the pharmaceutical field and in power engineering. The relatively high level of education and freedom from political preoccupations have been important contributing factors in developing a high level of both fundamental and applied research in Switzerland.

Characteristic of Swiss industry are the many small firms which conduct research. Most manufacturers using research have their own staffs for the purpose, but the watchmakers have a central research group which works on metals, alloys for watch springs, tools, new materials, and new processes for watchmaking.

Among the leading firms conducting industrial research are:

Society of Chemical Industry of Basle (dyes and pharmaceuticals).
Chemische Fabrik vormals Sandoz (dyes and pharmaceuticals).
J. R. Geigy, S. A. (dyes and pharmaceuticals).
Hoffmann-La Roche & Co. Chemical Works (pharmaceuticals).
Société de Produits Chimiques, Vetilron.
Aluminium-Industrie A. G. (aluminum).
Brown, Boveri & Co., Ltd., of Baden (electrical machinery).
Nestlé and Anglo-Swiss Consolidated Milk Co. (chocolate).

The Polytechnic Institute at Zurich, only postgraduate national technical school in Switzerland, conducts industrial research for the benefit of the nation as a whole. At the polytechnical school there is also a small but highly competent group engaged in pure physics research activities. It is especially well equipped for work in the field of nuclear research. Research has been conducted for some years there on coal, which is significant because Switzerland imports all its coal. The purpose of the coal investigations is to limit imports by selection of those kinds which most cheaply satisfy the particular uses for which they are employed. The institute recently erected a laboratory for industrial research to aid the development of Swiss industries.

As in the Netherlands, university professors often act as research consultants for manufacturers, who purchase the equipment and pay for such additional assistance as may be necessary.

The Swiss Government does little industrial research although it is active in agricultural research. The military technical service maintains a munitions testing unit and a laboratory for the study of war gases.

The number of scientific and technical societies in Switzerland is large.

Research in the Union of Soviet Socialist Republics

In Czarist Russia science was encouraged by the Government to a limited extent for its own needs including those of the army, and to present a showing to the rest of Europe, but to the great mass of the population it was nonexistent. Russia has produced great scientists, such as Mendeléef, famous for his work on the periodic law of the elements, and more recently Ipatiev, whose researches are the basis of hydrogenation of petroleum. The great scientists, however, accomplished their work largely because of their own interest and without recognition of science by the Government which depended for its needs in this field principally upon the work of Germany and France. Many foreign scientists and technicians were employed as consultants and all scientific apparatus was imported. Handicaps of publication of research results were great in the Czarist days. Before the revolution industrial research was practically nonexistent although noteworthy work had been done in platinum and petroleum. Scientific education began to be sought and new educational facilities served to train some of the first Soviet scientists. Many of the graduates, however, escaped from the country during the period of the First World War, the Revolution, and the civil war, and others refused to cooperate with the new system.

Under the Soviet regime science and research became part of the plan for the upbuilding of the new state. The initial problems of creating a Soviet science and technique, while at the same time solving the urgent needs of reconstruction, were exceedingly difficult. But ample money was provided and men were made available although for the most part poorly trained. Many foreign technicians and consultants were employed to assist in starting up new industries. Educational facilities were increased, many scientists finally cooperating upon realization that the new Government intended to permit them much greater freedom and importance than they had ever enjoyed previously. In the decade from 1927 considerable progress was made. Science and industry were closely coordinated, new technical schools, universities, and government research institutes were established. More recently, in accordance with the Soviet-German agreement, German scientists and technicians have been rendering services in production and technology, particularly in the fertilizer, textile, and petroleum industries.

The first basic difference between research in the Soviet Union and in Western Europe is its integral relationship with social life rather than any peculiarities of technical methods. The primary object of Soviet science is the welfare of the workers rather than an increasing profits from production. Workers are encouraged to assist actively in the application of science to industry. The second important difference inheres in the high degree of integration of Soviet science. The problems are not faced separately but as an interconnected whole. Science is synthesized into a unit—not compartmentalized—in its attack upon them. The relations of laboratories and institutes to universities and industry are carefully planned. The size of agriculture and industry necessary to produce the material needs of the population during the next 40 years are calculated. Appropriate provision is made for the equipment and research institutes required by each industry after careful study.

Coordination of research programs is accomplished by a series of committees, each of which lays out a general plan for each year. Conferences are held between representatives of fundamental and applied research on the one hand and applied research and industry on the other hand, so that a high degree of coordination is maintained between all branches of research and industry. These conferences serve to advance the Soviet policy of rapid introduction of inventions and research findings into industry.

The percentage of outstanding research workers in Russia is small. The huge number of poorly trained and mediocre researchers results in inefficiency, although the mass effort is bound to produce many useful results. Some of the contributions of research have been excellent, but on the other hand many are known to be unreliable and superficial.

In the Soviet plan of organized research the talents of individual research workers receive special consideration. For those who show unusual talent and ability, extensive laboratories are built, equipped, and staffed with as many men ranging from scientists to mechanics as may be necessary.

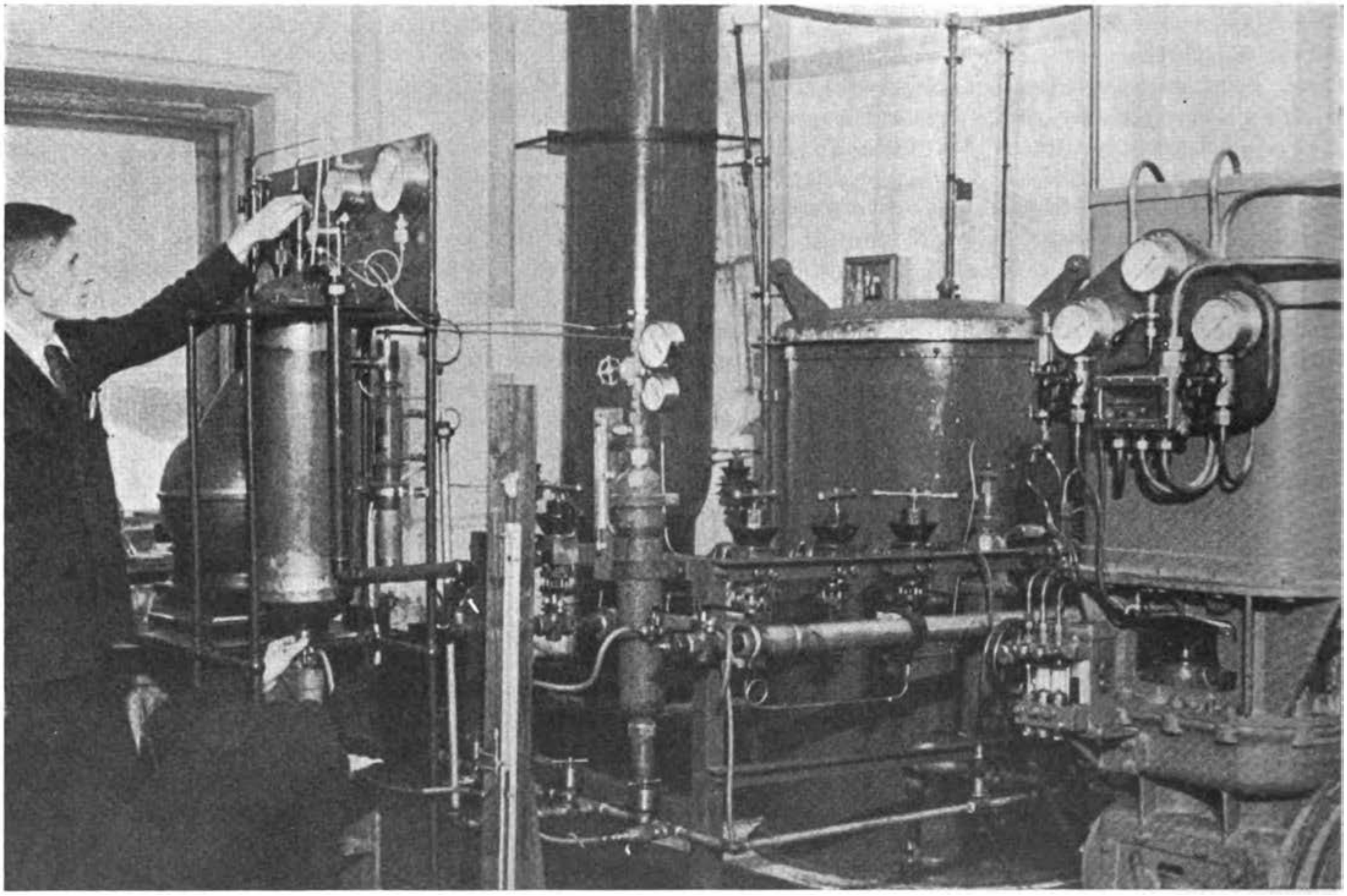
Research in the Soviet is not conducted with the expectation of early profits by any industry, consequently researchers are not expected to show immediate results. On the other hand, the variety of projects undertaken at some institutes renders the discovery of entirely new regions of physical knowledge more difficult than if concentrated on fewer lines.

The most outstanding feature of research in the Soviet is the magnitude of its operations. Bernal reports that the budget for science in 1934 was a thousand million roubles, a far greater proportion of national wealth than is devoted to science in any other nation.

The detailed and mass manner in which Russia undertakes a research problem is well illustrated by the coal sampling and testing project in the Don River Basin by the Coal Research Institute of Kharkov. These coal beds of many strata cover an area of perhaps 40 by 120 miles. Samples are taken at frequent elevations and submitted to many physical, chemical, and application tests, the number of which runs into millions. The project is costing millions of roubles. A staff of 80 chemists and physicists are employed on the project at Kharkov besides many field workers.

It is difficult to describe the structure of Soviet science because of the rapid changes that occur in its organization. The highest body in the State is the Supreme Council. Directly responsible to this body are the State Planning Commission, the Council of Peoples' Commissars (corresponding roughly to our Cabinet, although some members are responsible to state Supreme Councils rather than to the federal Supreme Council), and the Academy of Sciences, all of which are concerned with science and research in one way or another, in accordance with the Soviet policy that science must not be confined to one department but must be universal.

The duty of the State Planning Commission is to work out the details of the rational organization of social life so that knowledge may be used with greatest efficiency. It provides a framework for rationaliza-



Soviet Foto Agency

Figure 64.—Hydrogen Liquefier in the Cryogenic Hall of the Institute of Physical Problems of the Academy of Sciences of the Union of Soviet Socialist Republics

tion, among other things, of scientific research. An example of its activity is an exhaustive study of the strength of materials required for high tension electric lines and high pressure turbines. Such researches also lead to more fundamental investigations into the properties of matter.

In the Council of Peoples' Commissars, Commissariats having most to do with research are those of education, which is concerned with schools, universities, and science schools together with their laboratories; of health, which has direction over hospitals and medical research institutes; and those of the several industries.

The Commissariats of the industries are particularly concerned with research through their control of technical training colleges, the various research institutes in fields of pure science, the numerous industrial research institutes, and the factories and their laboratories.

Most of the fundamental research in the Soviet is conducted in research institutes such as the Physico-Technical Institute of Leningrad, the Institute of Chemical Physics of Leningrad, the Optical Institute of Leningrad, the Karpov Institute of Physical Chemistry, the Physico-Technical Institutes of Kharkov and of Dniepropetrovsk. Research in these institutes is concerned with the fundamental principles of the physical sciences underlying the technique of industrial processes.

Many of the Commissariats of the industries have their own industrial research institutes for carrying on research in the entire field of the industry concerned, such as oil, coal, nitrogen, shipbuilding, ferrous metals, nonferrous metals, chemicals, foods, textiles, and leather. In addition, several Commissariats have research stations or experimental plants for conducting research, including new processes, in the plant itself.

Fields of industry in which notable progress is claimed to have been made include aluminum from alunite and nepheline, phosphates from apatite in the Kola peninsula, potash, sodium salts at Karabugaz near the Caspian Sea, hydroelectric developments, high tension electric power transmission, automobiles and tractors, airplanes, gold mining machinery and technology, pharmacy, photography, rubber, metallurgy, milling and baking, sugar, subtropical products.

The Russian Academy of Sciences was founded by Peter the Great about 1724–25. There was no great change in its working organization until about 10 years after the revolution. Upon inauguration of the First Five-Year Plan the Academy was reorganized to advise on the many scientific problems arising from the changes in creating the new form of social life, and the remnants of the Czarist days were destroyed. Now its principal function is to coordinate the scientific activities of all the Commissariats as related to the planned economy of the Soviet. The Academy runs numerous laboratories engaged principally in long term research, and has plans for the erection of many new ones. Among the laboratories under its direction are the Biological Institute, the Institute of Human Biology and Medicine, and the Physical Institute.

Two of the best features in Russian research are the many research institutes which have been built, and as previously pointed out, the coordination and planning among all the agencies engaged in research, but the effectiveness of all this is a question upon which information is lacking.

Research in China

A movement for national science in China began about 1925. Since the occupation of a large part of the country by Japan, however, research has suffered a severe blow. Most of the capable scientific and technical men have had to devote their energies to other tasks.

The development of small industrial units in the interior of China, which has commenced since the Japanese occupation, is not conducive to research, consequently the Government and the universities are doing most of it. Nevertheless, in the remote western part, many scientists and engineers trained in the United States are engaged in development of unit operations as short cuts to industrial processes on a small and decentralized scale. In the Government the Department of Industrial Research was doing important work at Nanking in 1937, since when activities have been transferred to the interior. Metallurgy and motor fuel substitutes have been important subjects of investigation.

The Chinese universities are doing considerable work in applied fields and some in fundamental fields where objectives are expected to be obtained reasonably soon and benefiting industries such as leather, paints, and ceramics. The University of Peiping is mentioned in this respect.

Several technical and trade associations in China have been active, among them the China Pharmaceutical Society, the China Textile Institute, the National Medical and Pharmaceutical Association, the Chinese Chemical Society (which publishes a journal), and the Chinese Society of Chemical Industry (also publishes a journal). It is reported that the engineering societies in China have lapsed. Among these were the Chinese Institute of Mining and Metallurgy and the Chinese Engineering Society.

The National Academy of China was founded in 1928 for prosecuting scientific research and promoting and coordinating programs in the country. It has established nine institutes for the following branches of science: Astronomy, meteorology, geology, chemistry, engineering, psychology, history, and philology, and the social sciences. Each maintains a number of research fellows, associates, and assistants to conduct investigations and experiments under the general guidance of a director. In 1937 the appropriation for the Academy was $1,200,000. The Academy is doing much fundamental research, especially in telephony, radio, meteorology and physics. In applied research it is active in glass, aluminum from alunite, paints, sulfuric acid.

The National Peiping Academy, also founded in 1928, has two research institutes—for the physical sciences and technology, and for the biological sciences.

Other important research organizations in China are the Geological Survey at Peiping, the Fan Memorial Biological Institute, the Biology Institute, and the Science Society of China.

Research in Japan

The Japanese were not slow to recognize that science and research were responsible for the material progress of the Western nations, and adopted these means to further their own industrial development. The growth of research in Japan has been rapid during this century, especially in the last decade, and has advanced her to the rank of one of the leading nations in research. Indications point to continued progress in this direction. The research activities of Japan have largely followed the results of others. Emphasis of research has been on applied rather than fundamental aspects.

Bernal states that industrial, Government, and institute laboratories in Japan are probably larger, better financed, and better organized in relation to the wealth of the country than those of any other nation, but that the value of the work coming from them is more open to doubt. The organization of scientific research in Japan is based upon institutions and relationships usually found in Occidental countries. From Germany was adopted the plan of research institutes such as those of the Kaiser Wilhelm Society. From the United States was used the pattern of our National Research Council but with greatly expanded powers. Industrial research in Japan is extensively supported by the Government rather than by private enterprise. The indirect method of aiding new industries through partial stock ownership by the Government is also employed.

The scientific resources of Japan are distributed among many laboratories and institutes in departments of the Imperial Government and of the prefectures and municipalities; the universities and technical schools with their associated research institutes; numerous special research institutes, museums, libraries, botanical and zoological gardens; some 100 national scientific and technical associations; and industrial research agencies.

Within the Government itself upward of 70 research institutes are distributed under 7 different departments. Indicative of the broad scope of research activities which the Government supports entirely or in part are the following fields of investigation by some of the principal research institutes: Aeronautics, air navigation, aerology, meteorology, astronomy, seismology, geophysics, geology, agriculture, fisheries, forestry, horticulture, hygiene, tea, sericulture, zoology, ornithology and mamalogy, biology, chemistry, nitrogen, ceramics, fuels, brewing, steel, military research, naval research, railway research.

In fields associated intimately with the life and economy of the nation, Japanese research has accomplished notable results. The work of the Japanese Sericultural Experiment Station ranges from mulberry trees to silk itself. Japan is a leader in research on fisheries and pearls. Valuable work has been accomplished on camphor and menthol. It is interesting to note that at least three commodities—silk, camphor, and menthol, in which Japan had virtual world monopolies—have suffered in recent years from competition of artificial or synthetic counterparts. In two of these, silk and camphor, Japan has been compelled to turn to development of these new products. She has led the world in rayon production and is endeavoring to develop some of the truly synthetic fibers. Production of synthetic camphor is rumored to be projected.

In general, most Japanese research is directed toward self-sufficiency and preparedness. The last 3 years have witnessed special emphasis on finding substitutes for imported materials and the utilization of larger proportions of cheaper native materials with foreign. Manufacture of products not previously made in Japan, especially chemicals, has proceeded rapidly. Production of many synthetic products has closely followed foreign developments.

Industrial research by trade associations in Japan is very limited, owing in part to the large amount of research for entire industries being conducted in the various institutes.

Some of the results of Japanese research are disseminated in the form of lectures before technical or scientific societies, and some are published chiefly in the Japanese language but to some extent in English and German. Under existing wartime regulations, practically everything pertaining to industrial development and output is covered by the Military Secrets Law.

The number of research institutes in Japan is so large that space limitations prohibit their listing here. Activities of a few of the more important institutes will serve to illustrate the thoroughness with which the nation is employing research.

The Japanese Society for the Promotion of Scientific Research, founded in 1932, has among its objectives the encouragement and assistance of scientific study, assistance in the training of promising scholars, promotion of the use of new inventions and processes, conducting research for the development of industry, lending financial assistance to scientific expeditions, publication of scientific literature, and affording financial assistance for such publications.

From 1933 to 1937, inclusive, 2,048,379 yen had been granted by this organization for the pursuance of 1,797 scientific problems, divided 21.2 percent in chemistry, 10.2 in medicine, 10 in physics, 7.7 in mechanical engineering, 7.2 in agriculture, 6.6 in electrical engineering, 5.3 in zoology and botany, 4.7 percent in civil engineering and architecture, and the remainder in less technical subjects. Industrial subjects investigated included problems of spinning machines, liquefaction of coal, ship bottom paint, aircraft engines, tools and machines, power engines, chemical instruments, sand iron, mining, radio apparatus, active carbon, armor plate.

The National Institute for Physical and Chemical Research is a semigovernment institute established in 1917 with a fund of $2,950,000. Additional support is obtained from government subsidy. A few years ago the Institute consisted of some 27 laboratories for various subjects, each with its separate budget. Some of the laboratories are located in universities and at other institutions where the investigators are located. Facilities are said to compare favorably with those of such research institutes as our National Bureau of Standards, the Department of Scientific and Industrial Research in England, and the Kaiser Wilhelm Institutes in Germany. Industry defrays the cost of investigations in its behalf or supports fellowships for special work. The Institute is the largest center of industrial research in Japan. Recent activities include a process for manufacture of sake or rice wine, soybean sauces, vitamin A from cod-liver oil, and vitamin C from green tea.

The National Research Council of Japan was established in 1920 "to encourage and coordinate scientific and technical researches at home and to cooperate with other countries, with the view to promoting national and international researches in these fields." The members, who are appointed by the Government, are grouped in eight scientific divisions—astronomy, geophysics, physics, chemistry, geology and geography, biology and agriculture, medicine, engineering and mathematics, most of which publish journals.

The Tokio Research Institute Laboratory, financed by the Imperial Government, coordinates its activities with Japanese industry principally in the development of new processes and new products. It also has duties similar to those of our National Bureau of Standards.

The Imperial Fisheries Institute is supported by the Government for development of the fisheries industry. It investigates all phases of the industry, as zoology, habits and migrations of various species of fish, the nutritive value of fish, shellfish, and seaweeds, utilization of byproducts, improvements in processing technique, methods of capturing fish, design and equipment of fishing vessels. The Institute also renders educational services.

Other government supported research institutes are the Research Institute for Iron, Steel, and Other Metals of the Tohoku Imperial University, and the College of Fisheries at the Hokkaido Imperial University.

Development of the resources of Chosen, Formosa, and Manchukuo has been actively pursued by means of exhaustive investigations and researches. Separate organizations have been established for each of these areas. In Formosa work has been conducted on such subjects as pulp from bagasse, vegetable tannins, snake venom, and continues on camphor.

In Chosen the production of aluminum from alunite has been investigated, and production of carbon black from acetylene has been developed. The feasibility of growing agricultural products of industrial value has been extensively investigated.

In Manchukuo, the sponge iron and aluminum industries and alum shale as a source of aluminum have been under development. New outlets for the recently established magnesite industry have been sought. Rayon pulp from reeds has been developed. The research department of the South Manchurian Railroad has been the most active industrial organization engaged in industrial development in Manchukuo. It engages in both fundamental and applied research.

Research in Canada

Canada is industrialized relatively much less than the United States, consequently its industrial research is also less developed. The most important industrial research in Canada is concerned mainly with its natural resources and the products made from them. The largest enterprises are in mining and metallurgy, pulp and paper, utilization of agricultural products, and power generation. Consolidated Mining and Smelting, International Nickel Company of Canada, the Aluminum Company of Canada, Deloro Smelting and Refining Company, International Paper Company, the Howard Smith Paper Mills, Ltd., Lever Brothers, Procter and Gamble, and Shawinigan Water and Power Company, Ltd., are important organizations conducting research in these fields. Shawinigan Chemicals, Ltd., a subsidiary of the latter company, is very active in research on acetylene and derivatives, particularly vinyl resins. Imperial Oil Company, Ltd., is the only petroleum company extensively engaging in research.

Canada derives substantial benefit from the industrial research of American and British companies which own or control firms in Canada both with and without laboratories. The most prominent example of this is Canadian Industries, Ltd., largest chemical company in Canada, which is controlled by Imperial Chemical Industries, Ltd., and E. I. du Pont de Nemours and Company. The Canadian company is licensed to manufacture many of the products developed by the other two and receives the results of research carried out by them on such products. Canadian Industries, Ltd., also conducts its own research.

The Canadian Pulp and Paper Research Institute at McGill University, was sponsored by the Canadian Pulp and Paper Association which constructed a laboratory at a cost of approximately $400,000, and endowed the university with a fund of $100,000 to assist in carrying out research at the laboratory. The Association also provides additional annual grants for the same purpose, and contributes toward the operating expense of the Pulp and Paper Division of the Forest Products Laboratory of Canada. The Institute has been particularly interested in the utilization of lignin from pulp mills, including its use in plastics. A recent project of unusual interest involves production of liquid wood by a method of hydrogenation.

The National Research Council of Canada was organized in 1916 under the pressure of war conditions. Under the Act of Parliament which defines the duties of the Council, it is specifically stated that "The Council shall have charge of all matters affecting scientific and industrial research in Canada which may be assigned to it by the Committee" of the Privy Council. The President of the Council in his annual report for 1938–39 states that "The National Research Council lends its aid impartially to the producer in need of scientific assistance in the solution of industrial problems and to the consumer whose interests are best served when improved products are made available to him through the application of science to the betterment of his material needs."

The Council undertakes research for industry either cooperatively, as on projects of national interest, or at the expense of the industry concerned, when the work can be done more advantageously in the Council's laboratories than elsewhere. Inventions of the staff are available to industry on a royalty basis.

The National Research Council of Canada is a corporation which receives and administers its funds according to the act creating it, and in accordance with directions received from the Committee of the Privy Council for Scientific and Industrial Research of which the Minister of Trade and Commerce is chairman. Funds for its support are derived from appropriations by the Dominion Government, contributions toward special researches, royalties, fees, and from industrial organizations and private individuals. A laboratory costing approximately $3,000,000 was completed at Ottawa in 1932.

The Council is divided into six divisions as follows: Biology and agriculture, chemistry, mechanical engineering, physics and electrical engineering, research

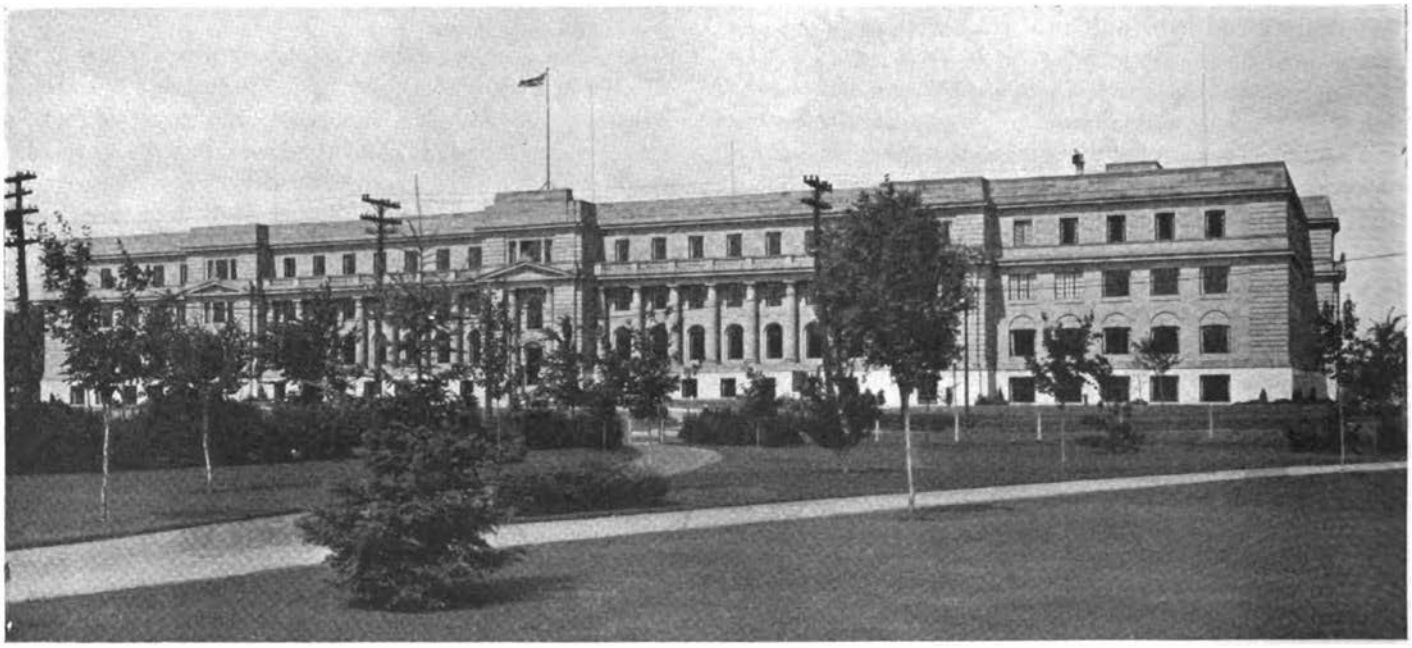


FIGURE 65.—Laboratories of the National Research Council, Ottawa, Canada

plans and publications section, section on codes and specifications.

Typical of research projects conducted by the Council in the last year are refractory materials from dolomite and calcium silicates, chrome brick, metallic magnesium, a simple process for extraction of radium from Canadian ore, production of rennet casein, production of face pieces for gas masks, corrosion resistance of aluminum alloys, efficiency of Manitoba bentonites for oil refining, and textile, laundering, and dry-cleaning investigations.

Early in 1940 perhaps 75 percent of the work under way at the laboratories in Ottawa had a war bearing, and over 60 definite war projects sponsored and financed by special war appropriations were in progress there and in outside laboratories.

In the last fiscal year 251 persons were employed in all the laboratories, of which number 103 were university graduates.

Two provinces in Canada, Ontario and Alberta, have research councils or foundations. That the Province of Quebec is becoming research-minded is indicated by the formation about 1937 of a commission for scientific research. One of its first duties was to take an inventory of the natural resources of the Province.

The Ontario Research Foundation was founded in 1928 by the Province of Ontario to carry on research work and investigations for the improvement and development of manufacturing and other industries, discovery and development of the province's natural resources including byproducts thereof; development and improvement of methods in the agricultural industry; scientific research and investigation for the mitigation and abolition of disease in animal and plant life and the destruction of parasitic insect pests; and generally the carrying out of other research work or investigations which may be deemed expedient.

The Foundation is divided into five divisions: Agriculture, pathology and bacteriology, textiles, engineering and metallurgy, chemistry, and biochemistry. In 1939 the staffs of these departments totaled 34 in number. Total expenditures of the organization in that year were $233,000.

The Research Council of Alberta was organized in 1921 along much the same but less ambitious lines as the Ontario Research Council. Its laboratories at the University of Alberta are concerned primarily with fuels and road materials.

The Dominion Government is active in research looking toward development of Canadian industries. Principal bureaus engaged in such work are the Bureau of Mines, the Bureau of Fisheries, and the Forest Products Laboratory. In many instances industries contribute to the support of research projects in these bureaus.

The Bureau of Mines encourages industry wherever possible, with research and investigative work in geology, mineral technology, and mineral economics. Mining operators make frequent use of the Bureau's ore-dressing and metallurgical laboratories.

The Bureau of Fisheries has done notable work for the Canadian fisheries industries, as in the development of the pilchard oil industry in British Columbia.

Of the Canadian universities which conduct research in applied fields the following should be mentioned: Universities of Alberta, Manitoba, and Saskatchewan for their research relating to provincial problems; University of British Columbia for its outstanding instruction of young men in applied sciences, especially chemical engineering; McGill University and University of Toronto for their graduate education in pure science, especially in physics and physical chemistry. The University of Toronto is particularly to be noted for its work on the electronic microscope.

Scientific and technical societies are very active in Canada. Among the foremost of these are the Royal Society of Canda, the Canadian Engineering Society, and Canadian Institute of Chemistry of which the Dominion chemical profession is justly proud. Most American scientific and technical gatherings are well attended by Canadians in spite of the distance, and there are in general very close relations between American and Canadian scientists of all kinds. The provincial academies of science are numerous and have published much good work.

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SECTION VI
MEN IN RESEARCH

Contents

SECTION VI

1. CHEMISTRY IN INDUSTRIAL RESEARCH

By Harrison E. Howe

Editor, *Industrial and Engineering Chemistry*, Washington, D. C.

ABSTRACT

This brief discussion points out the place of chemistry among basic sciences, distinguishes between the fields of pure and applied chemistry, and lists the following factors as those which motivate chemical research: Desire for new knowledge, dissatisfaction with a product or a process, hope of fulfilling a new need, possibility for utilization of raw materials or waste products.

It is pointed out that some industries—being born of research—pursue it as a matter of course and owe most of their success to such a policy. Forward looking executives initiate research seeking the advantages it is known to afford. In addition research is undertaken by those who are continually combatting or actively creating competition, and others obliged by law to do so, for example, those who must dispose of waste which is either a nuisance or a hazard.

The facilities for industrial research are discussed. These include laboratories of manufacturers, educational institutions, research foundations, endowed institutes and occasionally those of the Government, the services of consultants and sometimes of trade associations.

How research may begin is indicated, and the importance of the time element is stressed since this is often overlooked by those just beginning research.

A considerable portion of the chapter is devoted to accomplishments of chemical research. Examples include creation of new industries, breaking of monopolies, improvement of products, utilization of wastes, reduction of costs, discovery of new raw materials and new uses for old products, manufacture of new products, and invention of new processes.

Future trends are discussed from the standpoint of controlling factors. These include new techniques, competitive situations which may develop, and public opinion. Brief mention is made of fields in which greatest activity is expected in the future.

Chemistry and Its Field

Chemistry may be defined as the science which deals with the composition of matter and the changes it undergoes under various conditions of temperature and pressure. The chemist is particularly concerned with reactions between elements, their compounds, and mixtures. These reactions produce still other compounds, and today much of chemistry has to do with so controlling the direction and extent of these reactions as to produce satisfactory yields of predetermined new compounds.

Chemistry, physics, and mathematics are the basic branches of science. Chemistry is one of the fundamental sciences, hence it is but natural that its field of application is one of the broadest. This accounts in large measure for the early application of chemical research to industrial problems, its utilization in the broad fields of biology and medicine, and for chemistry as employed in plant control even where physical rather than chemical changes are involved. For example, chemical analysis is important in determining the properties of metals and alloys used in a machine shop where the transformations are almost wholly in the field of physics. The types of research in which chemistry is employed will be discussed later and in greater detail.

Two great divisions of chemistry—pure and applied—are still recognized, though often the borderline is indistinct. "Pure chemistry" is the term used to describe work undertaken primarily to expand knowledge in the science. It is carried on without reference to the possible practical application of the new truths discovered or of the new data established. It is science for the sake of science, and in the past there have been examples of workers who discontinued a chosen line of study as soon as it became evident to them that what they were doing had some industrial application. The declaration of Millikan that "all research to be justified must ultimately be useful" is recognized as sound by an increasing number of workers in pure science.

Kettering once said that the principal difference between pure and applied science lies in the fact that a pure scientist is seeking the answer to some problem without any particular urgency, while the worker in the applied field needs his answer and that in a hurry.

"Applied chemistry" is a designation reserved for work undertaken with some immediate utilization of the results intended. There is a definite accomplishment, a well defined goal, a practical problem in mind when the work is planned and undertaken. It is supposed to have a more commercial flavor than the so-called pure research.

There is no essential difference in the degree of difficulties confronting workers in these two fields and the demand is equally high for training and capability. Much of the best-known and valuable research in the United States has been done by men in industrial laboratories, and the same high order of accomplishment has characterized industrial research abroad. The line of demarcation is rendered still less distinct because men primarily engaged in pure science share the responsibility for applied science by engaging as consultants for industries, and often choosing subjects proposed by industry for the research problems of their graduate students. The arrangement is fortunate, because an insight into practical problems should make possible the improved training of men, the majority of whom later enter industry.

Research

Research is a scientific method for discovering new information which can be employed to extend knowledge in pure science and to the solution of industrial problems. It is a way to learn how to do that which has not been done previously by anyone. Those who undertake research should have an intimate knowledge of what has already been accomplished in their particular field, and their search should begin with the acquisition of such pertinent knowledge as is recorded in scientific literature and in patents. It is not uncommon to find research workers devoting as much time to a careful search of the literature as to experiments subsequently conducted in the laboratory.

FIGURE 66.—Research and Development Laboratories, Bakelite Corporation, Bloomfield, New Jersey. (Unit of Union Carbide and Carbon Corporation)

Incentives to Research

What gives rise to chemical research in industry? A necessary attribute of the successful research chemist is an inquiring mind. This does not imply mere curiosity but rather an intelligent desire for new knowledge with a view to its application to theoretical and practical problems. Some unusual phenomenon may have been noted and the man with an inquiring mind desires to ascertain its cause and its possible application. Learning why certain reactions take place usually leads to a knowledge of the factors involved which will enable the worker so to control the reaction as to produce the desired result. Oftentimes dissatisfaction with a product or a process initiates chemical research to ascertain what is wrong and how to correct it. The effort to meet a need very often leads to a research project. The researcher realizes that some demand would exist for a new product of certain characteristics. He designs it, and then develops a process for its production. The rapidity with which the market accepts the product is a direct measure of the accuracy in evaluating the situation. The desire to use a certain raw material is another motive for undertaking research. Utilization or prevention of a waste has become an increasingly important motive. Increasing cost of some raw materials is a factor but even more important is the stricter control of industrial operations in growing communities where the number of ordinary means of disposal become smaller. Some writers and commentators even place injunction proceedings and law suits in the list of motivations for certain types of research programs in industry.

There are still other factors that exert an influence in initiating research programs. There are those who are just naturally in research; the chemical industry, for example. Research is its outstanding characteristic. There is a constant effort in the chemical industry in particular to increase yields, to decrease and utilize wastes, to improve products, to lower costs, to introduce something new and useful upon the market, to manufacture and sell at lower prices and through increased sales still further to reduce costs. All this involves chemical research from start to finish.

A forward-looking executive also employs research to meet new competition, to avoid surprise which otherwise might seriously jeopardize his business, and to prevent being placed at a great disadvantage should others come to know more about his business than he does himself. In a sense every manufacturer is on the defensive unless his scientific and technical staff is ever alert. A considerable number of conditions can always develop to endanger an industry's position, no matter how strong. There is often the possibility of some new and cheaper raw material. A new process or improved equipment may entirely change the economy of operations. The demand and market for his products can be changed by the introduction of competitive products. New laws or regulations can quickly modify the industrial picture. After all, it is these uncertainties that keep business from becoming a rather monotonous game, and research accomplishments in any of these sectors not only result in economic advantages but provide stimulating satisfaction as well.

The Conduct of Industrial Research

Research in industry is conducted in many different ways, the most satisfactory depending upon varied factors. Many industries prefer to install their own laboratories and to proceed in their own way with or without the help of independent consultants. Some laboratories may be found where one man carries on the work with only the assistance of a laboratory boy to wash the glassware and collect samples. Indeed, in some instances the boy may be absent. The other extreme is a highly successful chemical company which in recent years has spent as much as seven million dollars annually on its research and development program. There are many research groups of different sizes between these extremes, set up in accordance with the needs of their organizations, well manned, well equipped, well housed, and doing important and profitable work.

Educational Institutions

Some industrial research is conducted in educational institutions, sometimes by members of the teaching staff who can devote a part of their time to such activities, and sometimes through fellowships maintained by the industry interested. There are certain advantages in this procedure, particularly in the lowered costs for the work and the fact that the holder of the fellowship may in this manner become especially trained to enter the employment of the sponsoring manufacturer upon graduation. However, there are certain disadvantages in that the student cannot receive from his professor all the assistance desirable, the work is not in close contact with the plant, and it is not always easy quickly to apply the results or where desirable to avoid premature publicity for what has been found. Perhaps the most important disadvantage is that the byproducts, i. e., skill, provocative suggestions, outgrowths, etc., of the research, fail to take root in the business for which the work was done. Patents present a particular difficulty and their control in connection with university work has caused a number of different procedures to be adopted.

Consultants

Some firms prefer to have most of their research done by consultants on a retainer basis. Ethical consultants seek to avoid complications by confining their attention to a single client in each field of manufacturing at a time, and by carefully respecting all confidences. The manufacturer utilizing the services of consultants can have his work conducted at a minimum of expense, or can invest in the research program as heavily as he sees fit. There is flexibility in the number of those assigned to his work, he avoids large initial expenditures in equipment and gains from the experience of those directing his work. Frequent reports as well as direct personal contacts with those directing the program can keep the manufacturer closely in touch with progress.

Government Laboratories

Of late years some industrial research has been conducted in the laboratories of the Federal Government through a system of associates. The arrangement obligates the manufacturer to pay the salaries of the men employed on his problem, and perhaps something for necessary materials, and gives him the advantage

FIGURE 67.—Research Laboratory, Monsanto Chemical Company, St. Louis, Missouri

of equipment, buildings, facilities, and direction which otherwise might not be available to him. The basis upon which such work is done varies in different departments, but in general the manufacturer has a minimum of control, the results are available for immediate publication, and the nature of the problem is usually determined by its general interest, since otherwise public facilities could not properly be made available. Some of the industrial research conducted in Government laboratories has been in fields where industry has been apathetic and needed to be shown by some practical demonstration the great assistance science can afford. In such instances the intention has been to initiate the work but not to carry it on indefinitely, in the expectation that the industry concerned would see the advantages of maintaining its own facilities for research and control.

Trade Associations

Oftentimes unsolved problems are so fundamental that their solution should be undertaken on behalf of all the individual concerns engaged in the same line of manufacture. Some of this work has been done successfully through trade associations which have built, equipped, and manned special laboratories for the purpose. The extent to which individual companies have profited or can profit from such enterprises depends directly upon the capabilities of their individual staffs. Obviously reports of such research mean little to the nontechnical man, but the company with the best scientific staff is in position to apply the new data at once, and thereby to obtain a substantial advantage over firms lacking good scientific departments. Trade associations have done much good work that has been of particular value to the smaller units in that trade which otherwise might not have profited from applied research.

Endowed Institutes

The endowed institute is, with one or two exceptions, a recent innovation. Some of these institutes have as a definite objective training men in addition to conducting applied research. This is a variation of the fellowship system, usually employs men who have graduated many of them with the highest academic degrees—and who are well paid by the donor to attack definite industrial problems under the direction of experienced investigators. Engaged on a salary basis, they sometimes have an opportunity to add to that income by a share in patentable results of their own work or by some other plan. If successful with their problem they often proceed to the industry for which it was solved, there to supervise the manufacture of a new product or the operation of a new process along the line of their research, or perhaps to continue the work in the private laboratory of the company.

Research Foundations

Recently, some educational institutions have set up foundations within their own organizations to carry on this type of industrial research, any profit augmenting the university's funds for fundamental research. It is obvious that the success of such plans cannot be uniform and that many factors influence them.

Another type of research organization is the research foundations, of which there are several in the United States. These foundations, for the most part, are engaged in fundamental research, with the advancement of science or the good of the public at large as their principal objective. They are well organized, amply financed, and their record of accomplishment is too well known to require elaboration here.

The question naturally arises—to what extent do these various agencies exchange information? Are the results of their work made public? Obviously the work done by trade associations, in certain types of endowed institutions, and certainly the results of research in Government laboratories, become readily available through publication and otherwise to those who have supported the work and frequently, in addition, to those known to be interested. But what about results achieved in private laboratories or supported by individual organizations?

It is true that many of these results are not released before patents are granted, or at least until application for patent is made. The reports of some work are not available to outsiders until whoever sponsored it feels justified in taking this step or unless the results are in such form that they will give no material aid to a competitor. That is a perfectly proper and natural business procedure. On the other hand the results of a vast amount of research are made freely available to all who are interested. Hundreds of scientific publications throughout the world regularly print such information. There are abstract journals which publish the meat of these articles regardless of the language of original publication.

The men who do the work congregate in frequent meetings, discuss papers, and exchange information in private sessions. The rapid rise in the technological and scientific level in some industries can be traced directly to a faltering beginning of open discussion between the research and technical men of the industry, who were at first brought together infrequently and who now meet semiannually under the auspices of the American Chemical Society or the American Institute of Chemical Engineers. There has been a marked increase in the willingness of the larger corporations to share with the smaller companies, usually without charge, some of the results of their own research. The establishment of "technical service" by those who manufacture a product or equipment has brought well-trained men into the plant of the consumer and made available to him the results of costly and time-consuming investigations. There are even financial organizations which make it their business to help by bringing the small manufacturer into contact with a larger one who is willing to share at least a portion of what he has learned through research.

Advertising agencies have been known to assist manufacturers to improve products or to devise new ones by bringing them into contact with consultants and other groups prepared to do research. The agency profited by handling an increased advertising account. The manufacturer who has never thought of industrial research as something within his means is frequently surprised to learn of the assistance he can get and the extent to which he can go within the limits of his purse, if he really becomes research-minded. Today there is a far greater exchange of information in the ways indicated, and in accordance with agreements made to exchange information, than is generally supposed. A ready exchange of information along some lines takes place through the medium of an informally organized group of research directors who meet frequently and discuss a variety of common problems.

Costs

The manufacturer, large or small, who first approaches the question of research will ask early in his investigations, "What will it cost?" The answer must differ in each case. Some types of work can be begun in small quarters with inexpensive equipment. Others may require a large investment in apparatus, much space, and a large staff of trained men. In addition to equipment and space, a cost of between $4,000 and $5,000 per man per year will care for the salary and supplies, including some special laboratory apparatus and equipment, stenographic work, etc. It obviously does not mean that all men will receive the same stipend. It is an average figure for a group. It will be obvious that research is one of those ventures that require much "educated patient money," to quote the late Dr. John E. Teeple.

The Time Factor

Patience is also needed between the time an idea is conceived and its result is in commercial production. Experienced men differ as to this time factor, but it is somewhere between 5 and 10 years, with perhaps 7 or 8 as an average. Even then it is not likely that perfection will have been attained, and research continues for years after a product has become commercial. Nothing is more discouraging to the research man than to be obliged to work under that type of constant pressure which reflects the cash-register attitude. It is not to be expected that research will begin at once to ring up the profits. Time is always an important element and short cuts to success are infrequent. It has been said that developing a new idea is somewhat like hatching an egg, and a hen cannot be hurried.

Organizing for Research

In initiating research two principal problems must be solved—preparation of a program of work and the selection of suitable personnel. There must be a careful choice of the problems to be attacked. From a large number of problems presenting themselves, those who know what is to be accomplished and who are familiar with the industry must make a well-considered choice and, having done that, can profitably go over the ground again and again. The president of a large chemical company recently said that, if a half dozen or so out of 200 suggestions initially proposed become really profitable after much time and money are spent in their development, his concern is well pleased.

With the problems selected, it is somewhat easier to determine the type of men required and recruit them with their specialties in mind. Specialists alone, however, are unlikely to obtain the best results. In any such group a man broadly trained in fundamental science will be found most useful. Long-established laboratories will usually be found to have teams of investigators prepared to devote their energies to the assignments given them by the director. And after years of work in a particular industry, the laboratory of such a firm naturally becomes adapted through a process of selection to the kind of work most likely to confront it.

There has been at least one instance where a well-to-do concern tried the plan of employing a considerable number of the best-trained men, most of them with good scientific reputations, in the belief that if such a group were given a well-equipped laboratory and worked there for a time, as seemed best to it, something revolutionary and profitable must be evolved. But there was no planned program for this highly trained group, and the undertaking was on such a grand scale that, before anything sufficiently fruitful could be evolved, funds became scarce and the scheme was abandoned. If it ever achieved success, such a scheme would have required years to show a profit.

Looking at research for the first time, anyone interested is likely to ask, "What has it accomplished to recommend it to me?" The answer can be a very long story. The rapid rise and expansion of industrial

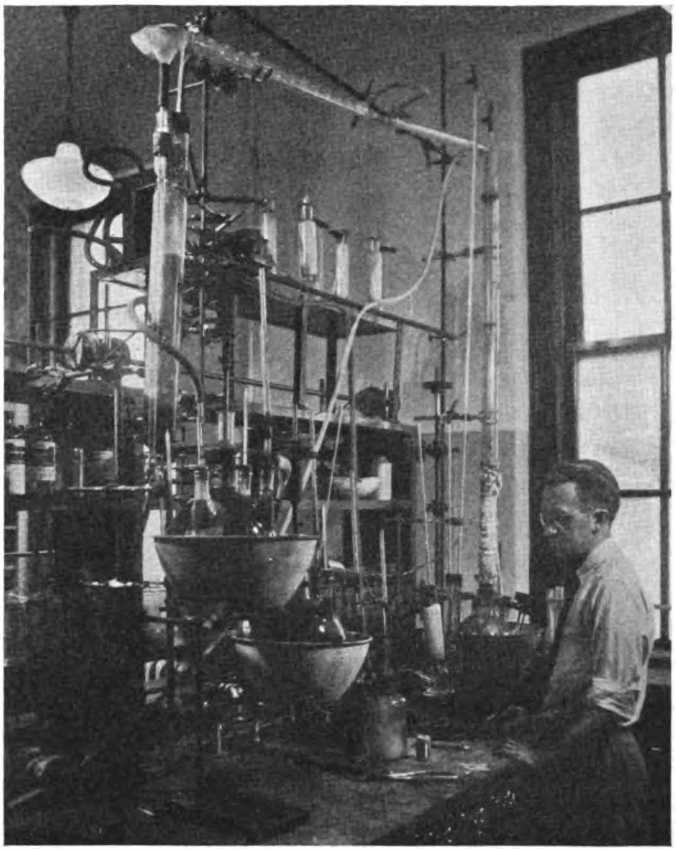

FIGURE 68.—A Chemical Research Laboratory, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware

America, especially in the last 25 years, can be attributed in large part to the intensive application of research. One important result is that still more research has been undertaken.

New Industries Created

Many new industries have been created. A modern example is in the growing utilization of fractions of petroleum, and, indeed, of individual hydrocarbons derived therefrom. Butane, propane, and pentane are among those raw materials that have lent themselves to the production of new lines of chemicals and the synthesis of well-known individual compounds. Today ethylene is made the source of many millions of gallons of alcohol, while acetone and even glycerin must be numbered among items synthesized from petroleum gases.

One of our best examples is the synthetic resin industry, because of its impress upon nearly every other industry. Early in our century the literature revealed some experiments in organic chemistry which had not yielded the product sought by the initial investigator, but which suggested to a reader a new line of research. The result was the synthetic resin, Bakelite, a condensation product of phenol and formaldehyde. That appeared in 1907, since which time whole new groups of resins have been introduced. Application of these materials has involved research and ingenuity almost on a par with the preparation of the resins themselves. New raw materials have been employed, additional characteristics have been imparted to the resins, and manufacturers are now quite likely to inquire first of all as to whether a resin will serve as a raw material before investigating metals, wood, or other substances.

The manufacture of rayon in its various kinds is well known as a new industry created through chemical research. Though begun with the pioneer work of Chardonnet in the gay nineties, it is still a subject of intensive research and the improved yarns and fabrics that are offered year by year to the consuming public indicate the success of that continuing program. Other kinds of synthetic fibers are now emerging from the research laboratories.

A new industry was created when chemists joined engineers in a search for the reason why internal-combustion motors developed a knock, and, having discovered the cause, undertook to provide a solution. Thus the manufacture and distribution of tetraethyl lead have become a new industry of great magnitude.

The chlorination of hydrocarbons for the manufacture of new solvents and of chemicals which until lately have been almost theoretical, or were at best produced only on a laboratory scale, is another instance of a highly successful industry built entirely on chemical research.

The list of new industries created through chemical research in particular could be made of great length, but the facts are well known, and social planners, economists, and those interested in public welfare have come to regard research as the most hopeful source of newer and bigger industries that would be potent in helping to solve the complex unemployment problem.

Monopolies Broken

Industrial research is often effective in breaking certain types of monopolies. It is more effective than legislation in accomplishing this end, because it achieves its objective constructively, finding new sources or offering equivalent products rather than destroying those already available. Let the demand be insistent enough or the monetary reward high enough, and research will be initiated to circumvent patents, to produce that which has formerly been a natural national monopoly, or to find a dissimilar material capable of performing the same service. The fixation of atmospheric nitrogen, now proceeding in all important countries, effectively destroyed the Chilean monopoly which had existed until 1912. Sir William Crookes' fear of famine due to a nitrogen shortage of fertilizers has long since vanished, and we now have a peacetime world surplus of fixed nitrogen. The availability of low-cost synthetic ammonia has given rise to new chemical processes, and the high-temperature high-pressure technique concurrently developed has become the foundation for new industries and the improvement of many old ones.

Camphor was the natural national monopoly of Japan until 25 years ago. The high prices during the World War enticed the research chemist to synthesize it, and methods were developed in Europe and the United States. The effort was sufficiently successful to bring the price back to normal. Further improvements have led to an abundant supply of both technical and U. S. P. camphor from American turpentine as the raw material, and today even Japan is considering the manufacture of synthetic camphor.

Another example is iodine, long a monopoly controlled by Chile and a byproduct in the manufacture of nitrate. Now this useful element is separated from the brines and bitterns of California, and Chile has lost the domination of the market. This is an incomplete list, but serves to show how chemical research in industry can effect changes that are international in their implications.

Improved Products

From the list of products improved through research, one need only choose examples from the results of the last year or two to emphasize the point sufficiently.

Shatterproof glass is of comparatively recent origin. The original cellulose nitrate interlayer was superseded by cellulose acetate which was less liable to discoloration, did not lose its transparency, and which could be made by a continuous process with less wastage. This was an improvement, but both these laminating substances were brittle at low temperatures and consequently did not then afford the protection expected of safety glass. Acrylic resin and vinyl acetate were also used, but in 1939 a polyvinyl acetal resin was perfected. This resin, which is exceedingly elastic and strong, is sandwiched between the sheets of glass without other adhesive, requires no edge sealing, retains its elasticity even at low temperatures, so as to absorb much of the energy of a blow, and objects striking such glass are much more likely to rebound from it than to penetrate it. This accomplishment has come about through cooperative research by several companies and is the reward for constant effort to devise a cheaper laminating material which would not suffer loss of transparency, which would resist discoloration, and remain elastic under a wide variety of conditions.

Varnish and similar coatings have been much improved by research on film-forming oils like china-wood or tung oil, the oils of other vegetable and plant sources, the most recent of which is castor oil. When dehydrated, castor oil becomes an excellent unsaturated drying oil, with properties that permit the use with it of optimum quantities of synthetic resins to produce a film of unusual wearing qualities. The story of lacquer is certainly now well known but is an excellent example of improving products through research. Modern lacquers were originally based on cellulose nitrate, and while vast quantities of this material are still used for the purpose, some of the newer alkyd resins are widely employed, and the user now enjoys a wide choice of these coatings to meet special requirements. The increase in the number of lacquers and their improvement has been a beneficial, though revolutionary, influence in the paint, varnish, and lacquer field.

In the textile field improved products have resulted from chemical methods for finishing yarns and cloth. The use of moisture-repellent finishes is now standard practice, and this treatment also confers a substantial degree of stain resistance. The use of certain synthetic resins increases resistance to creasing, and velvets are now produced that withstand crushing far better than previously. Textile printing has been improved by the use of synthetic pigmented resins dispersed in a water emulsion and fixed by brief heating following printing. The improvements in the textiles themselves are generally recognized, and while much of this comes from design in weaving, knotting, etc., chemical research has had its part in improving the raw material itself.

Work With Wastes

One of the activities of which the research chemist is most proud is the prevention of wastes or their utilization. While much of this work in the past has been undertaken for economy's sake, it is recognized that industry has some obligations to its community and should refrain from polluting streams, soil, and air. As the density of population increases, satisfactory waste disposal becomes a legal requirement in some areas. Cases often arise where the prevention of a nuisance is the sole reward the manufacturer can expect from the treatment of waste, but there have been a few cases where monetary profits have accrued.

The economics of waste utilization are too frequently disregarded. One of the best examples is to be found in the utilization of waste corn stalks, cotton stalks and the like, frequently proposed as sources of cellulose to be used in the manufacture of rayon or paper pulp. Anyone skilled in the art knows that chemical cellulose can be derived not only from corn and cotton stalks but from many other cellulose-producing plants. What is not so well known is that to produce a satisfactory grade of cellulose from these sources, including the cost of collection and storage of the raw material, costs much more than cellulose produced from wood and cotton linters. The nature of the latter is such that storage problems are minimized and the high concentration of cellulose in them constitutes an advantage difficult to equal.

There have recently come upon the market products from the waste sulfite liquor of the pulp industry. The material of principal value in this liquor is lignin, and foundry core binders and materials for highway construction have been two products from it. More recently, one mill has devised a method for the production of a low-cost plastic from sulfite liquor, and of synthetic vanillin which successfully competes in the market with that derived from coal tar. The recovery of sulfur dioxide and trioxide from smelter fumes from power plants has been successful. Sulfuric acid is the principal product, but if all fumes were so used so much acid would be made that it would become something of a nuisance. Elemental sulfur is also recovered from such sources.

The carbon dioxide formerly wasted from fermentation operations now finds sale as solid carbon dioxide or dry ice for refrigeration. The city of Milwaukee for some years has been able so to treat its sewage as to produce a fertilizer, the sale of which has materially lessened the cost of sewage disposal. The sugar industry finds a steady market for its waste molasses which is used for the growth of yeast and the production of alcohol. One of the great distilleries has devised a process for treating its waste, which must be kept out of local streams, so that the resulting feedstuff pays the overhead for the entire plant. Furfural, which finds extensive application in the purification of rosin and the manufacture of lubricating oils, to mention but two uses, is the result of waste product utilization, since it is derived from oat hulls.

Cost Reduction

The reduction of costs is always important in manufacturing. Two examples should suffice. In the slightly more than 50 years that aluminum has been a commercial metal, the price to the consumer has been reduced from 10 to 12 dollars per pound to the point where the metal in foil form competes with paper for making milk bottle caps and to provide individual cases for cigars. "Cellophane" cellulose film was introduced in 1926 and since then its price has been reduced voluntarily 20 times. Indeed, it has come to be recognized that the philosophy of the chemical industry is constantly to reduce the price to the ultimate consumer, for each reduction tends to broaden the market, increase the demand, and make possible a greater volume of production, by means of which manufacturing costs may be lowered further and selling prices reduced again. This is also true in the pharmaceutical industry and many examples could be cited to show how, through the procedure we are discussing, the ultimate consumer has reaped monetary benefit. This was accomplished not only without lowering standards, but generally with improved quality.

New Raw Materials

Industries are sometimes forced to find new raw materials and always benefit when they are found, if for no other reason than because they have a wider choice of materials and cannot be so easily subjected to price control. The development of dehydrated castor oil, mentioned earlier, will serve as an example. Its importance has greatly increased since difficulties in the Far East have interfered with the importation of tung oil. While the production of tung oil in the United States is increasing rapidly, the vast quantities required in the varnish industry still make necessary large imports. The dehydrated castor oil replaces much of this tung oil and thereby relieves that pressure. The castor beans for the production of this oil are normally imported— coming in greater part from South America, with some from India. Whether they can be produced on a commercial basis in the United States in competition with excellent growing conditions for perennial plants and cheap labor for harvesting the beans remains to be seen. A paper mill in New England has developed a satisfactory method for the production of pulp from hardwood, and by so doing has brought into the field of its raw materials great stands of satisfactory woods which, coming as they do from varieties not heretofore so utilized, add enormously to raw material supply. The work that has been done in the South looking to the use of southern pines, particularly for the production of pulp satisfactory to the rayon industry, for the manufacture of kraft, and now for newsprint, is a similar example.

One of the most conspicuous instances of finding a new source concerns the separation of bromine from sea water. This became imperative when the greatly increased demands for bromine arose with the use of tetraethyl lead. Until this development, our bromine was derived from the brines of northern Michigan. But this source was thought to be insufficient and, following pioneering research on the part of several groups, it is now recovered from the sea. Subsequent development has been very rapid.

New Uses

Another service to industry consists in the search for new uses that will increase the market demand for products. The diverse applications of synthetic resins offers one of the best examples. It has been found that urea, originally produced for fertilizer, later used as a raw material for a resin, promotes healing of wounds, and that pectin is efficacious in preventing bleeding at bodily surfaces. Liver, once a waste in the packing industry, has become the raw material for medicinal preparations, as has the pancreas, used in the production of insulin. And stainless steel has reached a new dignity in becoming the alloy for coinage in one of the European countries. It is also used as the palate portion of artificial dentures.

New Products

When we come to new products, the list could be made most extensive. One great company, reviewing the more important developmental lines over a 10-year period, discussed 12 groups of products, none of which had been in production at the beginning of the period. These 12 lines accounted for about 40 percent of the company's total sales volume for the year reported. Other industries can show variants of this ratio. At the moment we hear most of new fibers like nylon yarn, which has a higher strength-elasticity factor than that of any textile fiber now in common use, whether cotton, linen, rayon, or silk, to offer new competition for natural bristles used in various brushes, to become a coating material, and which will doubtless find many applications in other directions. Vinyon is another of the new fibers, resistant to dilute acids and alkalies, and therefore gaining in popularity as a medium for filtration. Glass fiber with surprising properties when one considers glass as it is ordinarily met is now available in colors and, as a nonflammable, enduring fabric, is pushing its way in competition with linen and cotton for draperies, table covers, and in the electrical industry as a competitor with asbestos. Kodachrome brings pleasure and instruction to millions, being the most successful of the photographic films reproducing a scene in natural colors. The vitamins, so mysterious 30 years ago, have been isolated in numbers as research has gone on and, of the 15 now recognized, 8 have been synthesized. Some of these are available at a price lower than when derived from natural sources. Vitamine B_1, now known as thiamin chloride, is available at such cost that it can be used profitably to aid the root development of plants. It will be used to replace vitamin B_1 removed from wheat flour by milling. A high B_1 yeast now on the market when used in amounts for leavening will restore the B_1 of white flour removed by milling. Indole acetic acid and propionic acids also function as synthetic auxins in promoting root development in vegetative reproduction of plants from cuttings.

The new medicinals that have been born of research are of greatest importance and comprise a very long list of their own. We hear much of sulfanilamide and its derivatives and rightly so, as measured by the results that have been accomplished. There is reason to believe, however, that the further development of these deriva-

FIGURE 69.—Main Library, The Dow Chemical Company, Midland, Michigan

tives may produce results no less startling than those that are on record. This planned group research is an excellent example of the modern method wherein instead of just continuing work with the hope of finding something useful, the objective is definitely outlined and careful plans are made for the campaign which should end in its achievement.

The necessity of finding a nontoxic and nonflammable refrigerant for use in large systems, not only for household refrigerators but for air-conditioning, led to the development of a family of fluorinated hydrocarbons one of which is dichlorodifluoromethane now called "Freon." This is an instance of an invention made to order to meet a distinct need. The wetting agents and detergents are new products of importance wherever aqueous solutions are employed, whether for textiles, dyeing and finishing, or in the laundries or machine shops for cleansing. The control of surface tension and the prevention of precipitation of the calcium and magnesium salts which cause hardness in water have come within the last decade and are used all the way from the removal of oil films from machine parts and laundering of clothes to dentifrices.

The synthetic rubberlike plastics are among the newer and most exciting materials of this sort and have long been sought by the research chemist. Neoprene, Thiokol, Koroseal, and Buna have become common names and represent various materials each of which is superior to natural rubber for some particular service. Butyl rubber, Chemigum, and Ameripol were introduced in 1940. So old a material as glass is constantly improved and new kinds made available. One of the latest of these is shrunk glass, produced by dissolving certain constituents from the finished molded ware and then submitting the resultant piece to further heat treatment. The final product is approximately one-half the bulk of the initial piece and in the process it acquires many of the valuable properties of fused silica. The field of insecticides is so important in our continuing battle with the insects that advances there are of public interest. Investigations showing how to separate and use active principles from heretofore little known plants like derris and cube have been very helpful. Research also has devised and continues to discover new organic and inorganic compounds that have proved very efficient against certain pests.

New Processes

New processes are not uncommon where chemical research is being applied. Ethanol, long derived only by the fermentation of sugars and starches, is now synthesized by the millions of gallons from petroleum gases. The most recent process for making urea produces that compound from carbon dioxide and ammonia. In 1939 methanol (crude natural) was produced by wood distillation to the extent of 4,659,589 gallons and by synthetic process from carbon monoxide and hydrogen to the amount of 34,255,699 gallons.

The contact process for the manufacture of sulfuric acid, using either the platinum or vanadium catalyst, has largely replaced the lead chamber method, and phosphoric acid is produced by new electrolytic processes. It was a new process for the production of phthalic anhydride that made possible at reasonable costs the production of large amounts required. New processes for the production of cyanide are more than merely interesting in view of the growing importance of that chemical as a raw material for many uses. Acetic acid and acetic anhydride are no longer made as they were even 25 years ago. Conversations with the manager of any chemical plant will reveal the fact that whereas the concern began by manufacturing its products in certain ways, marked improvements have been made through research with distinct gains in economy of operations. Simplification of processes and increased efficiency are the order of the day.

Materials for Equipment Construction

Many of these processes have had to wait for better construction materials and praise must be given those whose brilliant work has supplied such needs. Low-cost oxidation of synthetic ammonia to concentrated nitric acid was not possible until the advent of stainless steel. Glass-lined equipment, or that made entirely of special glass or fused quartz has been required for other processes. The ceramic industry has played its part in improving its wares and the production of entirely new equipment from clays and similar raw materials. Automatic control, improved methods of heating, the development of the exceedingly important high-temperature high-pressure technique are among the marvels of our time. Even advances in methods of transportation and improvements in packaging have all played their part in rounding out a procedure that has made the chemical industry itself and also as a contributor to other industries, so great and vital to the American people. It well justifies the designation of a "key industry." All of these things are fruits of persistent research conducted in continuity.

It is difficult to say in which fields the most has been done. If we use the publication of scientific papers and of patents as a criterion, we may gain some idea of the extent of research activity. If measured by the published abstracts of such scientific papers, we find first place in pure science belonging to biological chemistry, second to general and physical chemistry, and the third to organic chemistry. Industrial chemistry shows soils, fertilizers, and agricultural poisons first, foods second, pharmaceuticals, cosmetics, and perfumes third, dyes and textile chemistry fourth. If we turn our attention to the patent record, the chemical industry and miscellaneous industrial products stand first, dyes and textile chemistry second, metallurgy and metallography third, apparatus, plant equipment, and unit operations fourth. These are from a list of thirty classifications.

Promises for the Future

As for the future, we may quote Willis R. Whitney, who said, "The impossible is only what we have not learned to do." Research is planned and carried on today in a manner that affords the outstanding individual the support of an organized group of which he becomes the leader. An objective having been determined, a campaign is carefully devised to achieve it. Thus some years ago Irving Langmuir became interested in filaments for electric lights and in the electrical conductivity of gases and began his experiments accordingly. It was in the pursuit of this work that certain new data were established leading to the first of the modern incandescent electric lamps, wherein gases like argon are used in place of exhausting the bulb to a point approaching a vacuum. The result has been of enormous economic benefit to lamp users and the research has brought still other gains. Dr. Langmuir's work on thin films is another classic example of initial results of research originating with an individual and carried forward by him with the assistance of an appropriate research group.

New methods developed concurrently and in the hands of the well trained researcher offer new possibilities in the future. We have come to use procedures calling for infrared rays and X-rays, catalysis, in the solid, liquid, or vapor phase, very high or very low temperatures, not only in investigation but in actual production. New equipment of glass, stainless steel, clad metals, silver, ceramics, resins or any other material required is available as never before, and the giant vessels in which the cracking of petroleum and catalysis are carried on in many industries entitle the steel industry to a word of praise. New theories are no less valuable a tool than are possibilities of new equipment. Considerations of monomolecular layers, of atomic structure, of quantum mechanics, and of isotopes are useful and some of them so new that evaluation of their future trends is difficult. The importance of cumulative recorded experience must not be overlooked. Here again the scientific literature takes its place as perhaps the most important tool. The rapid progress of the day can be credited in large measure to the cumulative dividend the present enjoys on the work of the past. It is the recorded accumulation of some 200 years' research that is brought to play on today's problems.

Then too there are more and better trained men available than ever before and there is greater faith in the possibilities. The change in attitude toward applied research in industry that has taken place in this century is of the utmost significance. It is a change from conducting research in secret, and with some apologies for this evidence of supposed weakness in an organization to pleasure in advertising the fact that the pursuit of science by the best possible means is one of the greatest assets of an industrial organization. Once abandoned in time of emergency, today research is accelerated under similar conditions by farseeing executives. All these are factors in our new progress.

It is sometimes asked why so large a percentage of the research workers are in chemistry. This may be explained by the fundamental position that chemistry holds and consequently its applicability to practically all industry, as well as its utilization in most branches of science. Industry demands the continual development of new and better products. The industries need exact and specific knowledge of the properties of their materials, whether they are engaged in applied physics or applied chemistry. The methods employed by a manufacturer must be equal or superior to those of his competitors if he is to maintain his place. In all these circumstances chemistry is needed.

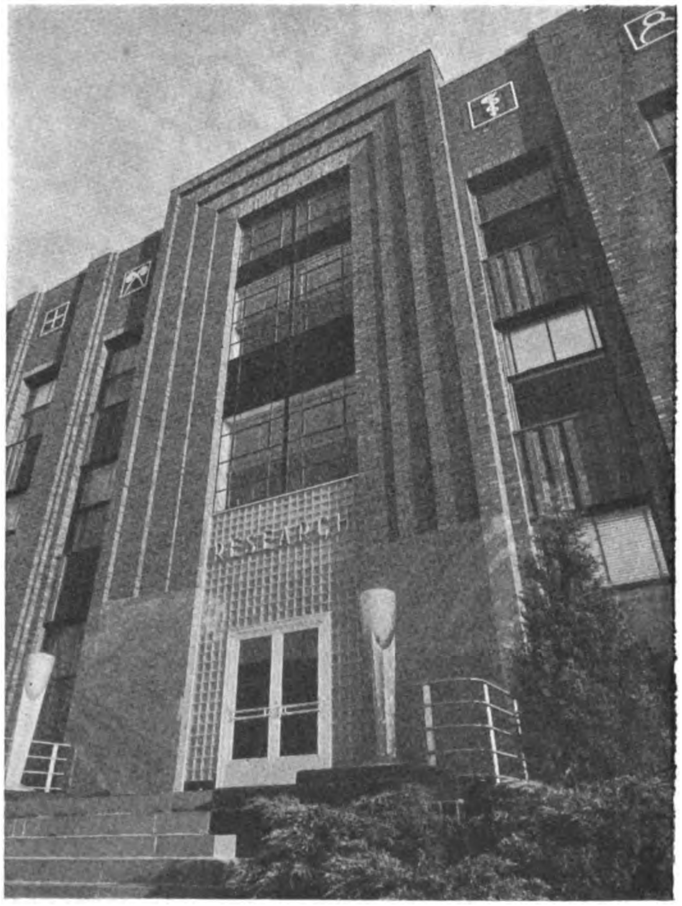

FIGURE 70.—Entrance to Research Laboratory, Abbott Laboratories, North Chicago, Illinois

The chemist has perhaps felt himself to be more a part of industry than have other scientists. In contrast with some other groups he was early engaged as a consultant and as an active worker on manufacturing problems. The pure and the applied scientist in this field have worked together more harmoniously and each has been more willing to credit the other with his contributions than in other countries or among other sciences in the United States. Perhaps the advances which it was able to bring about in the early days had much to do with attracting industry to the potentialities of applied chemistry and thus gave it something of a running start in its service to the manufacturer. Further and careful consideration of the types of problems upon which most manufacturers wish assistance seems to indicate that chemistry is and promises to continue to be one of the greatest possible aids.

It must be remembered too that the consulting chemist really pioneered in the specialty of being the someone to whom industry could go for assistance, and that the earliest popularization or humanization of science was done by chemists. All this must have had an influence on the trend that has resulted in so large a proportion of all those in industrial research having been trained as chemists. May there not also be some relation between the training of these men, who early learn analytical methods, learn how to distinguish between the important and the unimportant, how to watch for those small differences that so greatly determine final results, and the alert inquiring mind that characterizes the successful chemist?

Trends are influenced by public demands for improved and new products, by the success of new techniques, by competitive situations that call for the production of better materials and ways to circumvent the restrictions of monopoly, whether in the control of sources of raw materials or in the patented control of materials and processes, and by public opinion in many directions. The type of work discussed here is certain to continue as long as consumers are dissatisfied with present materials, as long as there is a demand for a greater variety of manufactured products and for something new, and as long as the scientist himself is motivated by the desire to know why things behave as they do. Chemistry applied in industry is in only the initial phase of its development.

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SECTION VI

2. PHYSICAL RESEARCH IN INDUSTRY AS A NATIONAL RESOURCE

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ABSTRACT

The profound influence that physics has had on human progress is illustrated by means of the steam engine, dynamo-electric machines, sources of light, and communication. From this is developed a definition of physics, and an orientation in regard to the field that should be included in the discussion. At present physics is deliberately made use of as a tool to help in the development of specific industries. This is illustrated by work in geophysics, in the lamp industry, and in communications.

Since physics is primarily a quantitative science, it has a great deal to do with measurements, and supplies practically all the measuring instruments used in the physical sciences, pure and applied. Many of the instruments and much of the apparatus that is developed by physics is not immediately applicable, but finds its application in later developments. Numerous illustrations of developments that are expected to find such applications are given.

Physics is a basic science, and much of the work done in physics is at least originally of a purely theoretical interest. Applications frequently follow even when the early results seem far removed from anything of a practical nature.

Finally, physics contributes indirectly to progress in many lines because it has an effect on the thinking processes not only of the scientist but of people who come in contact with his work. It produces an optimistic attitude towards problems, and a conviction that solutions can be found if all the facts are known, and are properly correlated.

In the last 50 years physics has exerted a more powerful beneficial influence on the intellectual, economic, and social life of the world than has been exerted in a comparable time by any other agency in history. In spite of this fact, however, many people do not know who the physicist is or what he does. The public is continually excited about this or that issue of politics, tariffs, codes, or international relationships which are of far less human import than the past and future of accomplishments in that body of science represented by—the American Institute of Physics. Its influence has far exceeded that of wars, political alignments or social theories.[1]

Many textbooks of physics begin with a prosaic definition of physics as the science of energy and matter. In fact, the subject is often treated in that manner, and students find it dull and uninteresting, and believe that like a dead language physics is unchanging and fully developed. It is our purpose here to show that this is far from the truth. Rather, physics is a vital living science, changing and expanding at an extraordinary rate. It enters every phase of our everyday life, and in research it offers industry an opportunity for fabulous returns on its investment. The developments of the past few years have been so startling that even a statement as strong as the one of President Compton, quoted above, needs but few examples to substantiate its truth. In what follows an attempt will be made first of all to show the place of physics in our everyday existence. Next, typical examples of the application of physics in the lamp industry, in oil prospecting, and in the communications industry will demonstrate the kind of scientist the physicist is and how he works. Finally, after a review of the use of physical instruments as tools in industry, an attempt will be made, upon the basis of the pure research now going on in university and similar laboratories, to suggest possible trends in the industrial physics of tomorrow.

Physics Has Profound Influence on Human Progress

The true value of physics in the past, present, and future development of our civilization is not easily estimated. Such devices as the wheel, the wheel and axle, the wedge, pulleys, time systems and means of measuring time, the compass, and many others were

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[1] Compton, K. T., et al. Symposium. Physics in Industry. New York, American Institute of Physics, 1937, p. ix.

developed before there were physicists or the profession to which they belong. Nevertheless the work of the inventors and of those who developed these devices was physics. They have become such an integral part of our civilization that it is difficult to imagine life without them.

The Steam Engine

It is difficult also to imagine modern civilization without some of the more recent developments in which the organized science of physics played a part. The early steam engine of Newcomen was very inefficient in transforming heat energy into mechanical energy and could hardly have become very significant industrially. James Watt realized that much more energy would be available if it were possible to let the steam expand in the cylinder before it was allowed to escape. As a result of this simple consideration, the steam engine became so much more efficient that it developed into a practical device. Because of its convenience as a source of power it contributed in large measure to the industrial revolution then in progress. The importance of the steam engine in ocean, river, and railway transportation, and in the production of electric power, gives evidence of the major role that physics has played in the development of modern industry.

Dynamo-electric Machines

Similar illustrations may be taken from other fields. The two physicists, Faraday in England and Henry in this country, began a series of purely scientific experiments which led to the dynamo-electric machines of today. These machines have made possible electrically powered transportation on both land and sea, electrical illumination that allows us to carry on practically all our activities at night as well as in daylight, and power for all types of electrical communication. The development not only of the elementary dynamo-electric machines themselves, but of their practical forms and of the systems making practical use of them, has been an accomplishment of physics and physicists.

Applications of Light

In the field of light we have illustrations of a somewhat different nature. Modern artificial illumination has been made possible as a result not only of the development of the dynamo-electric machines that supply the power, but also as a result of the development of light sources themselves. The step-by-step improvement of the incandescent lamp, which will be discussed later, with its rapidly increasing efficiency and decreasing cost, has resulted from the application of fundamental physical principles.

Many other applications of the science of light occur in industry. In ferrous and nonferrous metallurgy, the methods of spectroscopic analysis have become indispensable. These methods are based upon the fact that light can be separated into its component colors. When the source of light is a metal vaporized in an arc the colors can be separated still further into discrete lines characteristic of individual chemical elements. By spectroscopic analysis it has been possible to detect impurities in alloys and in supposedly pure metals and even to determine quantitatively the amount of these impurities. The importance of this method of analysis can be understood only by a full realization of the effect of small quantities of impurities on metallic systems and the occasional resultant failures of those systems. Spectroscopy has made possible the accurate, quick, and efficient analyses that are necessary for the control of furnace charges and for the control of alloy compositions.

In another type of analysis the invisible longer wave length portion of the spectrum is of use in studying absorption to determine very quickly some of the groupings in organic compounds. By this method it is possible to determine, for instance, the state or the condition of the oils used in paint vehicles, or of various types of gums or of lubricants, without having to decompose the organic compounds and try to put them through an ordinary chemical analysis, which is a very difficult and a long process. Study of progressive changes in organic compounds by this method is of enormous importance, as can be realized when one remembers the many organic materials that have become commercially useful in the last few years, as, for instance, plastic materials, of which there are at present hundreds to choose from, with all sorts of characteristics, and paint vehicles which change gradually upon exposure to increased temperature, variable humidity, or sunlight. The ability to follow the transformations in the formation and aging of such compounds provides an indication according to which the chemist can direct his course. Apparatus used for this purpose may be made to draw a curve which the operator soon learns to recognize, since distinctive shapes are caused by the presence of definite groups of atoms.

A very interesting recent application illustrates the way in which physics has invaded the field that was formerly reserved for the chemist. In the analyses for gaseous impurities, such as carbon dioxide in the air that we breathe, or of poisonous gases, it has been found possible by physical means to determine in a few seconds the quantity of an impurity in any sample of air even if present to the extent of only one part in a million. The analysis may be made continuously with permanent records. The apparatus is selective and can be arranged to read the amount of carbon monoxide, of carbon dioxide, or of any one of a great number of other individual gases entirely independently of the presence of other impurities. In this method also the selective absorption of light by different materials is basic.

Communication

Other illustrations of the way in which physics has contributed to our everyday life may be taken from the field of communication. In the physics laboratories of 35 or 40 years ago a great deal of work was done on the discharge of electricity through gases at low pressures. From these experiments, physicists learned of the existence of electrons and of their behavior under various conditions. They learned that an incandescent filament is a copious source of electrons and how to control these electrons. These studies led to the development of vacuum-tube amplifiers, without which our modern communication systems would be impossible. These vacuum-tube amplifiers form the basis of the communication equipment used in radio, in carrier-current telephony and telegraphy, and in any apparatus in which the current is too weak to operate instruments or apparatus directly. Thus there has been made possible not only longer overland communication but overland and transoceanic communication without wires or cables, the communication from ship to shore and vice versa, communication between trains and stations, between airplanes, between airplanes and their landing fields, and between police offices and police cars. These are all two-way communications. The currents set up in the receiving apparatus in each case are so feeble that their usefulness would be practically negligible without help from vacuum-tubes. It can be truly said that the whole art of electrical communication is a product of physics, and physicists have led in its technical advance.

The Nature of Physics

From the illustrations given above it is possible to develop a definition of physics and to give a fairly clear idea of what a physicist is and does. In its broadest sense physics includes in its scope the study of all the materials and forces of nature. It will have been noted that physics furnished the fundamental principles of the developments which have been described. The physicist also developed apparatus in which these fundamental principles were applied. The investigations in physics laboratories proceed from the discovery of a new principle and the study of its various applications to the determination of its place in the larger scheme.

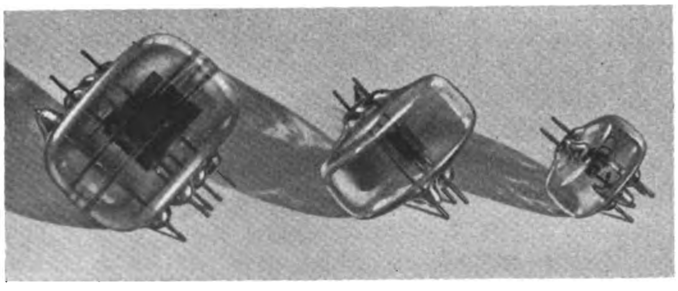


FIGURE 71.—Vacuum Tubes for the Production of Ultrashort Electromagnetic Waves, Bell Telephone Laboratories, New York, New York

When this work is successful it gives complete quantitative relations and enables one to predict what will happen under given circumstances and to set up the apparatus to produce desired results. If the phenomenon is a new one of wide application, such as the electromagnetic relations that form the basis of the development of dynamo-electric machinery, or such as the physical characteristics of metallic filaments that could be used in incandescent lamps or electronic tubes, the result is the creation of a completely new industry or even of many industries.

Physics has been described as the science of energy transformations, and if one studies the fields mentioned above it is seen that this definition applies very generally. Dynamo-electric machines, for instance, transform the energy of heat in the steam engine to electrical energy in the dynamo. In the motor, electrical energy is transformed into mechanical energy to be used in the apparatus being driven. In telephony the transformation is from sound energy to electrical energy, and back again to mechanical energy and sound. In instruments also it can be shown that in nearly all cases the action depends upon a transformation of energy from one form to another. In a clock the transformation is from the potential energy of a coiled spring or of raised weights to the kinetic energy of the pendulum and the moving wheels, and finally part of the energy is dissipated as heat through the friction of the moving parts. In all cases energy is transferred from one part of the apparatus to another, and in the transfer it is also frequently changed from one form to another. All such apparatus and instruments are products of physics.

Physics Specializes Effectively in the Problems of Individual Industries

The Oil Industry

In the oil industry one of the problems that has been attacked by physicists is the exploration for new oil deposits. The problem is to find rock structures that are typical of locations where oil is to be found. One approach to this problem is based on the fact that different layers of rock have different densities, and any initial deformation in a stratum relative to the other strata in the district will produce a change in the gravitational attraction for bodies on the surface of the earth.

As a background for this system of exploration there is, first of all, the determination of the general law of gravity, and, secondly, the development of instruments that are delicate enough to be influenced by any small variations in the distribution of the different rock layers. The general principles were known to university physicists long before any practical application was made in the oil industry. When it was realized that such a practical application could be made, the oil industry established laboratories in which groups of physicists were engaged in the work of making this type of exploration practical. First it was necessary to calculate from the law of gravity the results to be expected from typical rock deformations that were known to exist in oil-bearing districts. When it had been determined that, because of anomalies in the rock structure, the variations in the gravitational attraction for bodies on the earth's surface were great enough to be read on instruments, the next step was to develop instruments that were sufficiently sensitive and rugged and sufficiently quick in operation to be practical for field exploration. An instrument that reads gravitational force to 1 part in 10,000,000 must also be rugged enough to be carried on an automobile or a truck, and convenient enough to be set up at any field location and to allow a reading to be taken in a reasonable length of time. This means that the apparatus, among other things, must be insensitive to minor vibrations and to temperature changes that are likely to be encountered in the field. Many types of apparatus were developed which met these requirements, and as a result of this work the amount of gravitational exploration that had been done in the last few years is many times as great as that which has been done by all methods during all the rest of the world's history.

After these measurements have been made to determine gravity, it is necessary to map and to interpret them in terms of subterranean structures. Again, a very complicated application of physics and mathematics, together with geology, is required. The physics, taken together with the mathematical calculations, describes the possible structures insofar as their densities and locations are concerned, and the geology interprets the structure in terms of the likelihood that oil is present. These methods can be applied also to exploration for other types of minerals whenever they are associated in any way with variations in densities and vertical positions of rock layers.

Magnetism has been known for many hundred years, especially as applied in the use of a magnet as a compass. University and other laboratories have been studying the magnetic characteristics of materials over a long period of time. It has been found that not only iron and compounds of iron, but practically every type of material has measurable magnetic characteristics. It is known that igneous rocks which form the substratum under all sedimentary rocks are more strongly magnetic than the latter. Hence it is possible to use sensitive magnetic apparatus to determine approximate depth and slope of the upper surface of the igneous substratum. The story of this type of exploration is very similar to that mentioned above, insofar as it is absolutely dependent on the development of sensitive apparatus to make measurements. An industrial physicist is employed to carry the development on from the point at which his academic brother left it. Apparatus is produced which is sensitive, rugged, and relatively unaffected by vibrations and temperature variations. The physicist is familiar with this type of development and has the benefit of the work of many predecessors who have overcome similar difficulties in other circumstances.

Another procedure used in geophysical exploration is the study of the transmission of mechanical waves or of sound through the subterranean structures. A charge of dynamite is exploded in a hole that has been drilled to the necessary depth to give it adequate contact with the rock layers. The compressional wave produced by the explosion is transmitted through the earth and comes to the surface again in other neighboring locations after being bent because of the gradual changes in wave speed in underlying rocks or after being reflected at the surface separating rocks of one structure from another having a different wave speed. Here again it was necessary to develop sensitive apparatus not only for recording the arrival of compressional waves but also for recording the time that elapses between the discharge of the dynamite and the reception of the wave at a distant location. The data obtained can be used in many ways to determine the subsurface contours of various rock layers, which, together with geological knowledge about the neighborhood, give even more direct and useful information than that obtained in gravitational exploration.

All three methods of exploration are used by the oil companies at the present time. Although the formations discovered do not always contain oil, the probability of finding oil is considerably increased over that which obtains when wells are drilled at random. The cost of drilling is so great that even a small increase in the probability of finding oil makes the exploratory research carried out by the physicist worth many times its cost.

Of the many other applications of physics in the oil industry we mention only two. Until a few years ago it was a common experience that when a deep well was drilled by the rotary method the hole would not be straight. The drill would gradually veer in one direction or the other, so that the location of the bottom of the hole was indeterminate. A physical study of the cause of this uncertainty made it possible to develop a cure. By means of a rigid guide above the drill bit and by the accurate control of the pressure on the drill, holes can now be sunk to any required depth without significant change in direction.

Another very important and profitable study that has been made by physicists is concerned with the flow of oil in rocks. Oil is usually found in a variety of porous rocks such as sandstones or limestones. The rate at which it can flow through a porous rock was determined in the laboratory. From these studies the rate at which oil can be removed from deposits of limited area without restricting the total output is now understood and may have considerable economic importance.

It is perhaps worth emphasizing again that what physics has done in the oil industry is to teach the principles that are applicable, to develop instruments that are sufficiently sensitive and rugged to make measurements in the field, and to interpret the measurements in terms of subterranean structure. It has changed oil prospecting from a matter of chance to an exact scientific procedure which has enormously increased the availability of sources of oil.

The Lamp Industry

The application of physics in the development of the various types of illumination in the last 30 or 40 years provides another example of its use in industry. It was early realized that electrical energy may be used to produce light. The simplest and the most direct way to accomplish this is to allow the electrical energy to heat a solid to incandescence. The most convenient form that such a solid could take for this purpose is a long, high-resistance filament, and the earliest practicable filament was the carbon filament originally developed by Edison. It had its imperfections in that the temperature at which it could be operated was low, its life was short, and the color of the light produced was reddish. The ambition to produce a more efficient filament from these standpoints stimulated the work on tungsten and other materials. Much of this work is of a physical nature and was carried out in physics laboratories. Many things had to be studied. First of all, it was found impossible to draw tungsten into a fine filament. Cooperation between physicists and metallurgists finally resulted in the production of ductile tungsten.

Then began the most interesting part of the development. A careful study of the radiation, the effect of the temperature of the filament on the nature of the light emitted and on the life of the filament, gradually provided information that became useful. Originally the filaments were operated in a vacuum. A study of the effect of the presence of inert gases on the evaporation and the deterioration of the filament showed that it was advantageous to surround the filament with such a gas at appreciable pressures. The presence of the gas retarded evaporation and permitted the operation of the filament at a very much higher temperature. The higher temperature produced whiter light, and also resulted in the emission of a greater portion of the energy in the visible part of the spectrum, giving a higher efficiency. In the construction of these lamps it was necessary to apply physical apparatus and measuring instruments in many ways. It was necessary, for instance, to study metal-to-glass seals so as to produce a perfectly airtight bulb in which the filament could be housed. This necessitated the comparison of coefficients of expansion of various kinds of glass and metal and the development of combinations of glasses and metals to make seals that were absolutely tight at ordinary temperatures and that remained so during the heating and cooling which the lamp experiences in use.

The study of the radiation from the filament itself required the use of optical pyrometers, with which it was possible to determine the exact temperatures of the filament at any one spot. To avoid false readings from the surface, the filaments were made tubular and the temperature of the interior was read through very minute holes through the side of the tube.

Photometric measurements were necessary to determine the light intensity of the source. To obtain useful information these measurements had to be made in all directions from the lamp, thus enabling one to integrate the total radiation either mathematically or by means of integrating photometers. A spherical photometer, with which the total amount of light in all directions could be determined by a single reading, was one of the physical developments that resulted. It was desirable also to determine the distribution of light throughout the spectrum. This feat was accomplished by applying the photometer to individual portions of the spectrum in an apparatus known as a spectrophotometer.

In the early stages of the development of the modern lamp, the research laboratory assigned itself the job of finding out everything it possibly could about heated filaments. One of the discoveries was that the inert gas used in the lamp formed a sheath around the filament and thus decreased the rate of evaporation. By coiling the filament springwise this protective sheath became more effective, and the efficiency was increased. The rather novel suggestion was then made to coil the coil into sort of a superspring. On trial, it was found that this procedure increased the efficiency still further, and it is done in making most of our lamps of today.

This brief history of the research on the incandescent lamp illustrates well how the physicist works. Ordinarily he is not trying to make minor improvements in design. Instead he studies the fundamental process of converting heat energy into light. As a result his progress seems slow. He is not able to predict beforehand just what he will find or what changes he will make. Yet he can always be sure that the more he knows about these fundamental processes the greater is his chance of producing a major improvement. In the lamp industry each improvement took from 5 to 10 years of research, yet each repaid the company many times over for its investment. Since the time of Edison the efficiency of the lamp has been improved almost a thousand percent. It has been calculated that if Edison's lamps were used to produce our present illumination our annual light bill would be $3,500,000,000 greater than it is at present.

A more recent development in light sources goes back to another branch of physics; namely, to the electric discharges in gases at low pressures. In the nineties of the last century, experiments with such tubes were very popular in physics laboratories. Although these experiments were performed without immediate practical purposes in mind, it has been found in the last few years that the light so produced may be used as a source of very practical illumination. The color produced by the passage of electricity through a gas depends upon the nature of the gas, and different gaseous combinations give varied light effects. The striking colors produced are used extensively today in advertising. High-intensity mercury and sodium vapor lamps are used for airport and highway lighting, searchlights, and other purposes. By introducing fluorescent materials into the glass tube in which the discharge is taking place it is possible to produce colored and also nearly white light with extremely high efficiency. The various stages of development from the discharge tube to a practical source of light with an efficiency considerably greater than that of the incandescent filament is a long and interesting story, but in its essentials it is similar to that of the incandescent filament lamp.

The Communications Industry

The field of communication has already been mentioned as one in which the application of physics has been important. In a wire as in a radio telephone the sequence of operations calls into play an unusual number of physical principles and also a vast number of different types of apparatus used to transform physical energy. The sequence is about as follows: The voice produces disturbances in the air which move the diaphragm of a microphone. The diaphragm produces a change in pressure on the carbon granules assembled in a capsule, and thereby produces modulations of the current through the carbon granules. This current is sent out on the line either directly or else amplified through vacuum tube amplifiers to increase its power. If it is desired to transmit several messages over a pair of wires at the same time, so-called carrier telephony is used, in which the voice current changes or modulates a carrier current of a higher frequency. After the modulation it may again be amplified and passed to a telephone line or cable, or in the radio telephone, to a radiating antenna. If the receiving station is far away there may be vacuum-tube repeaters to pick up the message and transmit it at a higher power level. At the receiving end another filter picks one message out of a great number, an amplifier increases its power, a demodulator separates the voice frequencies from the carrier frequency, and finally an earphone or the loudspeaker directly transmits the sound to listeners. Thus, the telephone is a peculiarly good example of the fact that physics is the science of energy transformations. The following sequence of energy transformations are represented: Mechanical energy of the vocal cords is changed into mechanical energy in the form of compressions and rarefactions in the air, which is then used to energize the diaphragm of the microphone. This energy is transformed into electrical energy of the same frequency by the action of the diaphragm on the carbon granules. The electrical energy is amplified, modified, and transmitted over the line or through space. During these steps the electrical energy is progressively changed, but it remains electrical or magnetic until it reaches the diaphragm of the earphone or the loudspeaker. Here it is transformed into mechanical energy again. The diaphram of the loudspeaker agitates the atmosphere and the listener receives the mechanical rarefactions and condensations in the air on his eardrum.

The remarkable developments in telephone communication have resulted from the convergence of physical investigations in many different fields. First of all there have been the investigations of sound production by the vocal cords and of the modification of that sound by the shape of the mouth and related cavities. Methods of analysis of sounds, both vocal and instrumental, have been developed to determine their component frequencies, the relative energies in these frequencies, and the ways in which they combine and can be reproduced and separated out again as a result of the compound vibrations or responses of electrical, magnetic, electronic, and mechanical devices.

Other investigations that have converged on the effective transmission of sound have been the study of responses of diaphragms and of their construction so as to make the responses as nearly uniform as possible over the audible range, and the study of the behavior of masses of carbon granules, both as regards the resistance of the mass and the variations of these resistances with pressure, and the reproducibility and permanence of such resistance changes. The contributions of the early experiments on electrical discharges in gases have already been mentioned. As a result of the study of the behavior of hot filaments, the discovery has been made that electrons are given out by incandescent solids, that these electrons will carry currents, that the number emitted depends upon the nature of the hot surface, and that they can be controlled by a very small amount of energy applied to an adjacent electrode. These discoveries resulted in the development of the vacuum-tube amplifier, without which modern loud distance communication would be impossible. Likewise electromagnetic and crystal filters were developed, which enabled the communications engineer to select from the complete range any band of frequencies that he wished. A very important series of investigations concerned magnetic characteristics of materials that could be used as cores for transformers and for loudspeakers, or earphones, and of the permanent magnetic materials that were used in combination in some of the later types of apparatus.

These studies of fundamental principles and the development of materials and apparatus to provide efficient means for the necessary energy transformations are in the field of physics. Thus we have an example in which many different branches of physics have converged to produce one practical accomplishment of immeasurable value to society. On the other hand, in many cases a single development in physics, the vacuum tube for instance, has produced entire new industries and has found practical applications in almost every industry.

Physics Supplies the Instruments for Measurements in Industry

One of the many accomplishments of physics has been the development of instruments. For instance, in aviation we have measuring instruments for determining the direction of flying, the orientation of a plane, the location of a landing field when "flying blind," the speed of the plane, the drift of the plane, the distance from the ground, etc. Many different devices have been developed for each one of these purposes, and all are based on a direct application of physical principles. That the instrumentation has already reached a high state of development is evidenced by the remarkable safety records of our commercial air lines.

Such applications of instruments and measuring devices in any particular field could be multiplied practically ad libitum. We shall, however, content ourselves with mentioning a few specific instruments which are in regular use at the present time.

Noise meters, a development which has been contributed to largely by the telephone development described above, enable anyone to determine the level of disturbing noises in an industrial plant or on a street, to determine the origin of the noises and in that way to supply the first essential knowledge toward their elimination.

Another interesting instrument that has come into use in the last few years is a vibration meter, which can be applied to any piece of machinery to determine the magnitude, direction, and exact nature of its vibrations and to lay the foundation for the elimination of the undesirable vibrations.

X-rays serve many purposes, such as finding blowholes in castings, faults in rolled steel, or faults in welds. They can be used also for analyzing crystals or determining the exact crystal structure of a material, and even the distances between the atoms in the different layers of the crystal. X-rays are of great importance in metallurgy and in the physical study of structural materials.

The cathode-ray oscillograph is a recent addition to instruments that are useful for studying electric circuits. It depends on the action of an electric or a magnetic field on a beam of electrons and makes it possible to observe at a glance the wave form or the nature of the distortion in an electric current produced by any piece of apparatus that is subjected to study. The cathode-ray tube is used in television, position indicators in flying, and in many other applications.

The sterilizing effect of ultraviolet radiations of certain frequencies has been investigated by physicists in cooperation with biologists and others and has resulted in the development of a lamp which produces radiations of a frequency peculiarly adapted to destroying infection or undesirable germ life of any kind. It is applicable in medicine, in the food industry, in the purification of water, and in the sterilizing of eating utensils.

Physics Prepares Apparatus for Later Applications in Industry

Instruments of great value to industry are often born in the laboratory of the pure scientist. In an effort to extend the frontiers of knowledge new instruments or new methods of developing extreme pressures, high speeds, high or low temperatures, etc., are discovered which go far beyond what are considered present needs of industry. It seems profitable to review some of the present procedures of the laboratory to find those most likely to be used more extensively in the future in industry.

High-Speed Centrifuge

High rotational speeds have long held the interest of physicists. Recently, new advances in experimental technique have allowed rotational speeds as high as 20,000 revolutions per second to be obtained. The only reason for this limit is that the rotator flies apart at appreciably higher rotational speeds. The centrifugal forces that occur at the edge of such a rotator are almost inconceivably large. A force 8,000,000 times that of gravity is possible. If the force of gravity were as great a dime would weigh more than 16,000 pounds. To obtain such high speeds, the rotor is mounted in a vacuum, supported by an external stream of air and driven through a flexible shaft connected to an air turbine.

So far ultra-speed centrifuges of the type described have been used primarily in biological fields. The forces are so great that heavy molecules can be separated from light ones. Thus tobacco mosaic and yellow fever viruses have been concentrated and hormones have been isolated. Wherever rapid settling of liquids or sediments in liquids is required, the ultracentrifuge has been very useful. So many new lines of work have been opened in biological and medical fields by the new techniques in high rotational speeds that it is practically certain that a multitude of industrial uses will appear as soon as the possibilities are fully understood.

Cyclotrons, Van de Graaf Generators, and Geiger-Counters

The intensive study of the atomic nucleus by academic physicists during the past decade has led to the development of many new processes and instruments. Perhaps the most striking discovery of all is that high-speed ions are able to transmute one chemical element into another. Many of the materials formed by this transmutation have, in addition to the ordinary properties of the new elements, the characteristic of being radioactive like radium. Thus by bombarding ordinary table salt by high-speed atomic particles a radioactive form of sodium can be produced which for some medical purposes is more valuable and much cheaper than radium itself. Nearly every chemical element can be made radioactive; thus one can have radioactive iron, copper, zinc, tin, etc.

Two different types of machines have been developed to produce radioactive elements. In each the essential purpose is to produce high-speed atomic particles which upon striking ordinary elements produce transmutation. One of these machines is the cyclotron, so-called because it makes the atomic particles move in a circle and brings their speeds up to the desired value by a small increase each half revolution. Twenty or thirty cyclotrons, each costing from $20,000 to $1,500,000, have been, or are being, built in this country. The demand for radioactive materials is so great, however, that many more will need to be built very soon. The second type of machine for producing high-speed atoms is the Van de Graaf electrostatic generator. This is essentially a direct-current generator that develops a potential of from 3 to 5 million volts, This high voltage causes charged atomic particles to crash down a tube with such speed that some of the atoms of any element placed at the end of the tube will be disintegrated. Four or five such machines, costing up to $150,000 apiece, have been built in this country. While their primary purpose is to study nuclear structure they may possible be used industrially in many other ways in the future. For instance, there is much discussion regarding the transmission of power by high-voltage direct current. It has even been suggested that the "atom smasher" of today may be used for the commercial transmission of electrical energy tomorrow.

Radioactive materials produced by the cyclotron and the electrostatic generator are useful in medical therapy. They can be used in industry for testing thick welds in the same way that radium and X-rays are now being used. Their most important use arises, however, because of a new instrument known as a Geiger-counter, which has been greatly improved in recent years Radioactive elements exhibit their radioactivity because of the continual emission of high speed fragments or high energy radiation. Each of these fragments can produce a discharge in a Geiger-counter, thus enabling single particles from radioactive elements ("tracer atoms") to be counted. If one, for instance, drinks a solution containing radioactive sodium, it is possible by means of a Geiger-counter to measure the time it takes for the sodium to enter into the blood stream and reach the finger or any other part of the body. Likewise calcium can be traced directly from an individual's food to his teeth. Of industrial importance is the possibility of tracing by radioactive atoms the diffusion of copper atoms in iron, gold, or even in copper itself. There must be many industrial processes in which tracer radioactive elements would be useful. With the modern Geiger-counter the tracing of 1 part in 100,000,000 or even more can be carried out with certainty by simple standard equipment.

Color Analyzers

Color is used in almost every industry, yet its exact definition is essentially unknown. Manufacturers of paint, ink, cloth, paper, glass, and other commodities give names to colors even though they realize that these names can in no way specify the color exactly. A dye manufacturer who makes one batch of color 1 year cannot match it a year later because his original samples may have faded. To remedy these defects in the specification of color the physicist has designed a colorimeter which draws a curve which is characteristic of each specific color alone. If two samples of materials have the same color curve, they will be found identical in color not only by daylight but also under all forms of artificial light.

This instrument is called technically a "recording spectrophotometer." It measures and records automatically the reflecting power or the transmission of a given sample for all wave lengths in the spectrum. Many manufacturers of inks and other materials wherein color must be specified exactly are already using this instrument to make precise colorimetric measurements.

Electron Microscope

Much research has been carried out in the last few years on the paths that electrons take when accelerated by grids and rings in tubes. It has been found that certain arrangements of electrodes or coils have exactly the same focusing properties for electron beams as glass lenses have for light beams. Thus it is quite possible to build electron microscopes that are superior to optical microscopes for some purposes. This is particularly true where a heated metal is being observed. Such a metal emits electrons which can be accelerated by applying a small voltage. If these electrons impinge upon a flouorescent screen they produce an optical image that shows variations in the composition or condition of the surface of the metal. Since the lengths of the electron waves can be made as small as desired, there is no limit to the theoretically possible resolution which can be achieved, as there is in an optical microscope. The electron microscope should have many applications in metallurgical and other fields as its properties become better known.

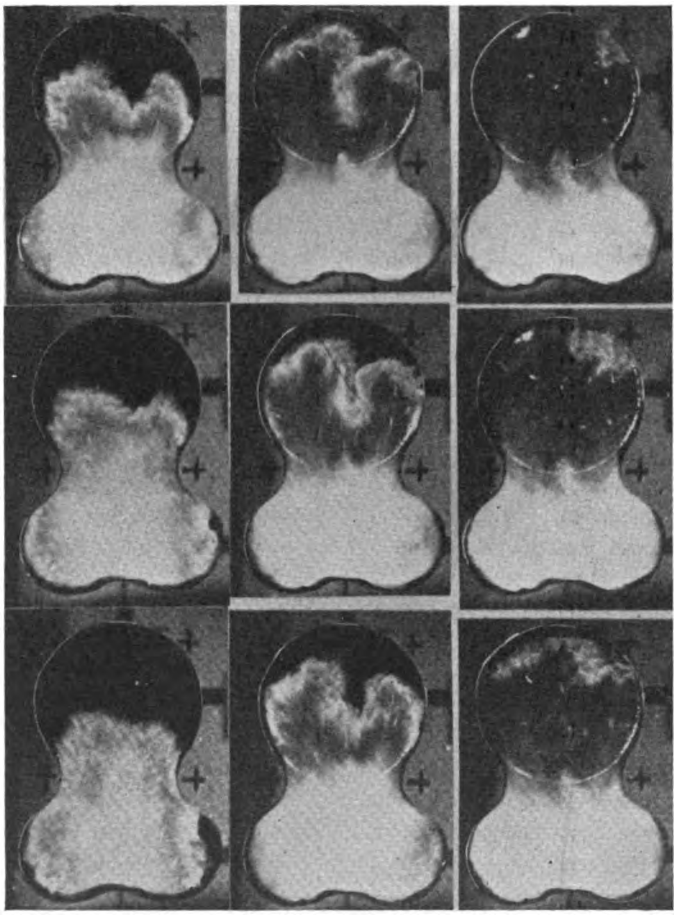


FIGURE 72.—High-Speed Photographs of Combustion in Gasoline Engine, General Motors Corporation, Detroit, Michigan

High-Speed Photography

For many years high-speed photographs, particularly of sound waves and bullets in motion, have been taken by the light of the electric spark. Until recently this photography has been confined to the laboratory, since it was difficult to obtain sufficient illumination to take ordinary pictures. It has been found, however, that a violent discharge of an electrical condenser through a gas-filled tube provides an intense flash of light of very short duration. With such a flash extraordinary pictures of objects in motion can be taken. Striking examples of pictures of a swinging tennis racket, golf club, or other sports equipment have been published in the popular magazines and newspapers. A succession of such pictures show in detail, for instance, how an air bubble is formed by a drop splashing into a liquid surface, or the way in which a golf club is bent in striking a golf ball. Although industrial applications of high-speed photography do not receive the publicity of these other applications, there have been very many useful applications, and there will undoubtedly be many more. In the textile industry great difficulty was caused by the snagging of the thread coming off a very high speed spindle. The speed was such that it was impossible to see what made the thread catch. However, a high-speed photograph showed immediately that a loop was being formed as well as how this loop became entangled. In the airplane industry high-speed photography permits the direct measurement of the distortion of a full sized airplane propeller. Although the propeller rotates at full speed, it is possible to obtain a precision of 0.02 of an inch in these measurements. The design of silent fan blades was aided by high speed pictures of the formation of vortices using smoke mixed with the air.

Photoelasticity

With increased competition in industry, the elimination of excess weight has become a very important factor. To determine the size of any part of an engineering structure and exclude unnecessary material one must know how the stresses are distributed. The mathematical calculation of the stress distribution in an irregularly shaped member is often so difficult that only a rough approximation can be made. To obtain more exact analysis of the stress distribution a method has been devised making use of polarized light. This method of analysis has received considerable stimulation in the past few years by the introduction of the material known as "polaroid," which enables large beams of polarized light to be formed at low expense. If one uses two sheets of polaroid with their axes at right angles to one another, no light will penetrate; however, if a celluloid model of a particular engineering structure is placed between those two sheets of polaroid and a load is added, the points of maximum stress become bright with closely spaced bands of color. It has been possible, for instance, to reduce greatly the weight of an eyebolt by cutting away those parts shown under polarized light to be of little use for carrying the stress. By careful measurements with polarized light combined with accurate measurements of the change in thickness, it is possible to make a complete analysis of the distribution and magnitude of all of the stresses. This is particularly easy to do in thin and plane objects, but by recent methods can also be done for objects of irregular dimensions.

Electron Diffraction

A remarkable discovery was made in an industrial research laboratory a few years ago. This discovery was that an electron behaves as though it has associated with it a wave length in the same sense that light waves and X-rays have wave lengths. When electrons pass through a thin layer of any material or are reflected from its surface and allowed to impinge on a photographic plate, they make a permanent record of a diffraction pattern similar to what one sees when looking at a distant light through an umbrella. The pattern is characteristic of the material placed in the path of the electrons. An electron diffraction camera is a relatively

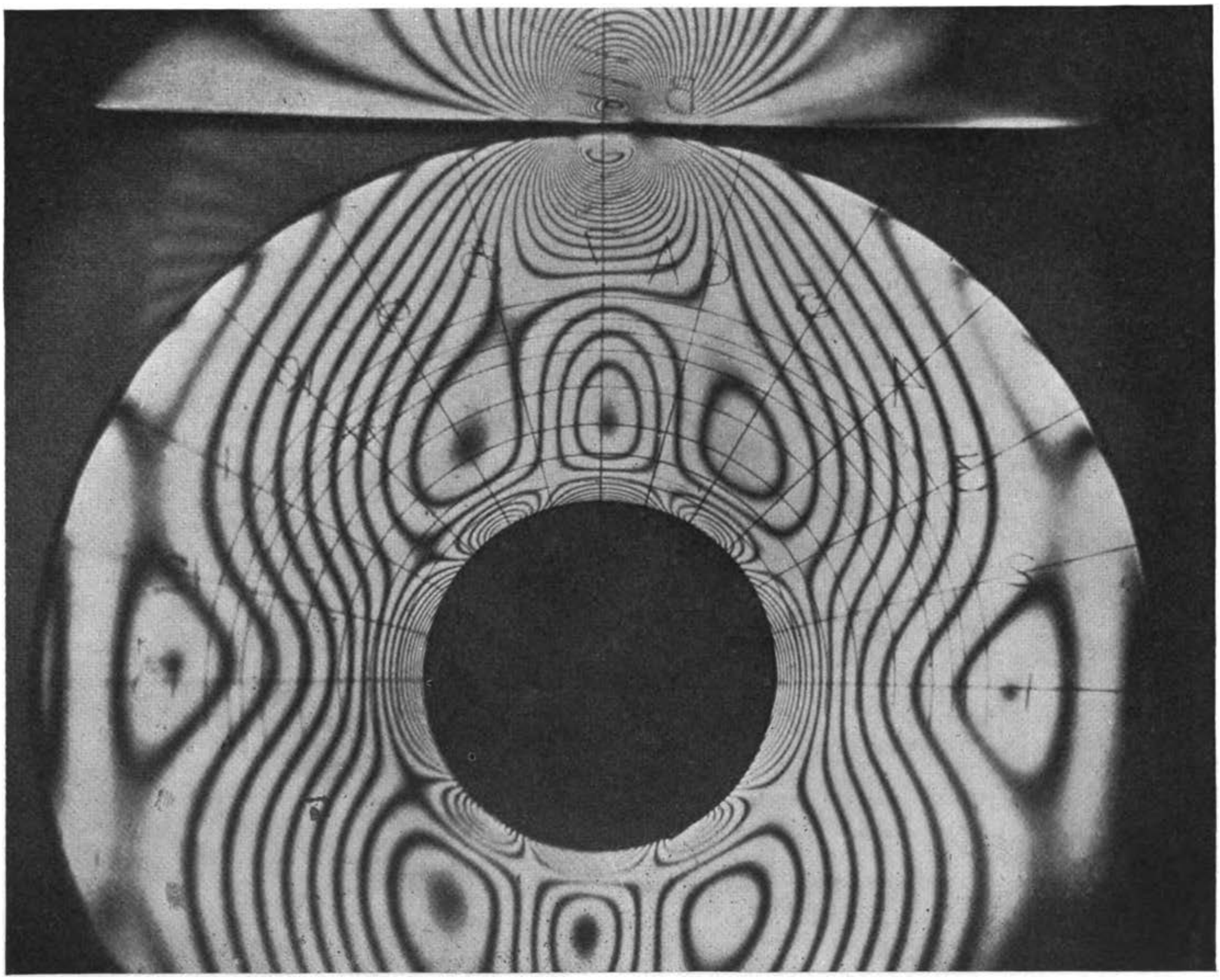


Figure 73.—Photoelastic Pattern of Roller Bearing Stresses. Points of Maximum Stress Occur Where the Lines are Spaced the Closest, Timken Roller Bearing Company, Canton, Ohio

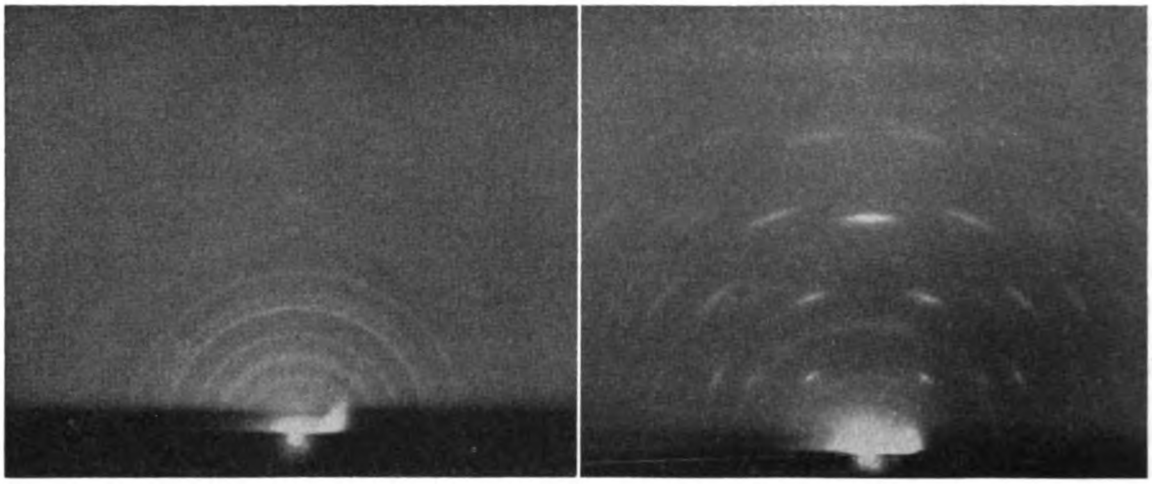


Figure 74.—Electron Diffraction Pattern of (*a*) Plated and (*b*) Stripped Metal Surface (after H. R. Nelson)

simple piece of equipment. It is only necessary to have a heated source of electrons and a high-voltage supply to accelerate them in a tube. Since the electrons are scattered primarily by surface atoms, while X-rays are scattered deep in the metal, electron diffraction is most useful in studying surface properties. It has been used, for instance, to identify various oxide coatings, tarnishes, and other corrosions produced on the surfaces of metals. If one wants to know the structure of an electroplated surface, electron diffraction can usually give the answer. Until recently it has been difficult to determine exactly the structure of thin films because X-rays pass through them so easily. Electron diffraction on the other hand tells us a great deal about the structure of these thin films. Polished and buffed surfaces are increasing in importance in industry and electron diffraction provides evidence as to whether such surfaces are crystalline or amorphous, and also as to the changes in a surface as buffing progresses. These are only a few of the possible applications of electron diffraction in industry. Wherever the nature of a surface comes into question, use can be made of this tool.

Extreme Pressures

A very interesting curve has been drawn showing how the largest obtainable pressure has increased with time. This curve has started upward rapidly in the past few years; in fact, it has more than doubled in about 3 years. It is now possible to study in the laboratory pressures up to 1,500,000 lb./sq. in. It may be wondered why it is desirable to study such extreme pressures, but when one realizes that enormous pressures often occur in industry in hypoid gears, ball bearings, glass cutters, and rifles, the interest is understandable. Many strange phenomena occur at extremely high pressures. For instance, chemical reactions that do not take place at ordinary pressures can sometimes be promoted by an increase in pressure. Under high pressures it is possible to bend glass without breaking it, to precipitate colloidal particles from a solution, and to produce many other unusual effects. Studies have been made of the penetration of liquids and gases into solids. It is found, for instance, that under great pressure hydrogen penetrates into steel sufficiently to decrease its tensile strength by more than one-half. A recent important industrial study has concerned the effect of extremely high pressures on lubricating oils. In fact, it is only because of the development of lubricants working well at extreme pressures that the use of hypoid gears in automobiles has become possible. In view of the great number of

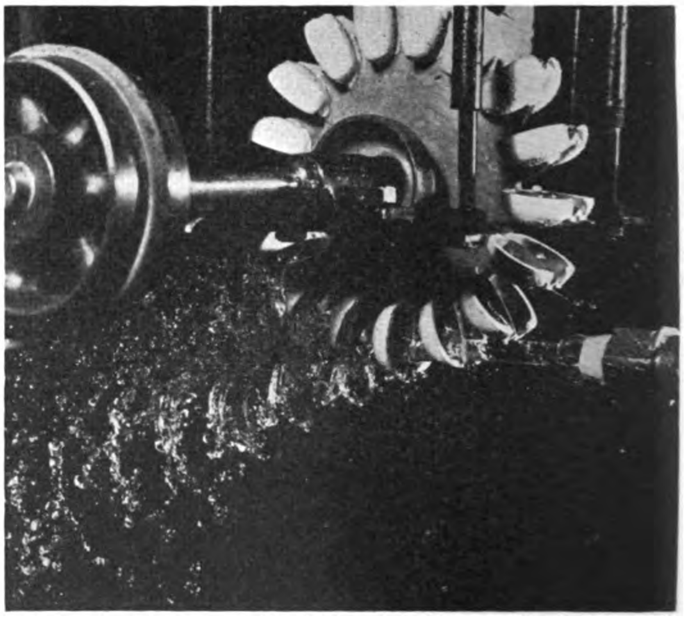


Figure 75.—Motion of a Pelton Wheel Frozen with the Aid of High-Speed Photography (after Harold E. Edgerton)

unusual effects produced at extremely high pressures, it is anticipated that such investigations will lead to many applications in industry.

Extreme Temperatures

Advances in experimental techniques of all kinds sooner or later become useful in industry. It is probable, therefore, that the extremes of temperatures recently attained in the laboratory will find many industrial uses. For instance, recent methods of cooling by using a magnetic field have led to the production of temperatures only a small fraction of a degree above the absolute zero. At these temperatures the electrical resistance of many materials drops to zero so that a current started in a loop of wire will continue for many days without any supply of energy. With such temperatures all gases can be liquefied. One type of liquid helium exhibits a very unusual property of having almost zero viscosity; this means that it will flow through tubes under a very small pressure gradient.

At the other end of the temperature scale progress has also been made, for instance, in the development of blocks to stand the high temperatures that occur in a glass-melting tank. In the laboratory it has been possible to achieve temperatures up to 20,000° for short-time intervals by exploding fine wires. While these high temperatures have not yet become of commercial importance, they offer considerable possibility for the future.

Fundamental Explorations Provide the Bases of Future Industries

Physics is outstandingly a practical science and there is very little that the physicist discovers that does not eventually come into practical use. The person who applies the discoveries of the physicist is usually an engineer. While the engineer is making the application, the individual for whom the name physicist is reserved is busy discovering new phenomena which will probably be applied by the next generation of engineers.

Thus to learn what kind of physics will be applied in the future one can hardly do better than to observe the fundamental discoveries now being made in the pure research laboritories in the universities, in industry, and in the large governmental departments.

Nuclear Physics

In the universities it is quite apparent that much of the pure research is concerned with the atom. Many physicists are engaged in trying to understand the structure of the atomic nucleus. Mention has already been made of the artificial radioactive elements produced as a byproduct of these investigations, and which are so useful as tracers. Besides radioactive materials it has also been possible to produce gold, silver, helium, and other stable elements by the transmutation of less valuable materials. Although at present it does not seem likely that these processes will develop into practical sources of materials in quantity, the investigations will pay for themselves many times in the uses that have already been mentioned. Other valuable applications are very likely to follow.

There is still another commercial possibility which may arise from the study of atomic nuclei. It has been discovered recently that when uranium is bombarded with either slow-moving or very fast-moving neutrons (atomic particles with no charge), elements are produced which have approximately half the atomic weight of the uranium and at the same time a new batch of neutrons is liberated. The new elements are emitted at tremendously high speeds, and thus have a large amount of energy which can be transformed into heat. This experiment immediately suggests that if

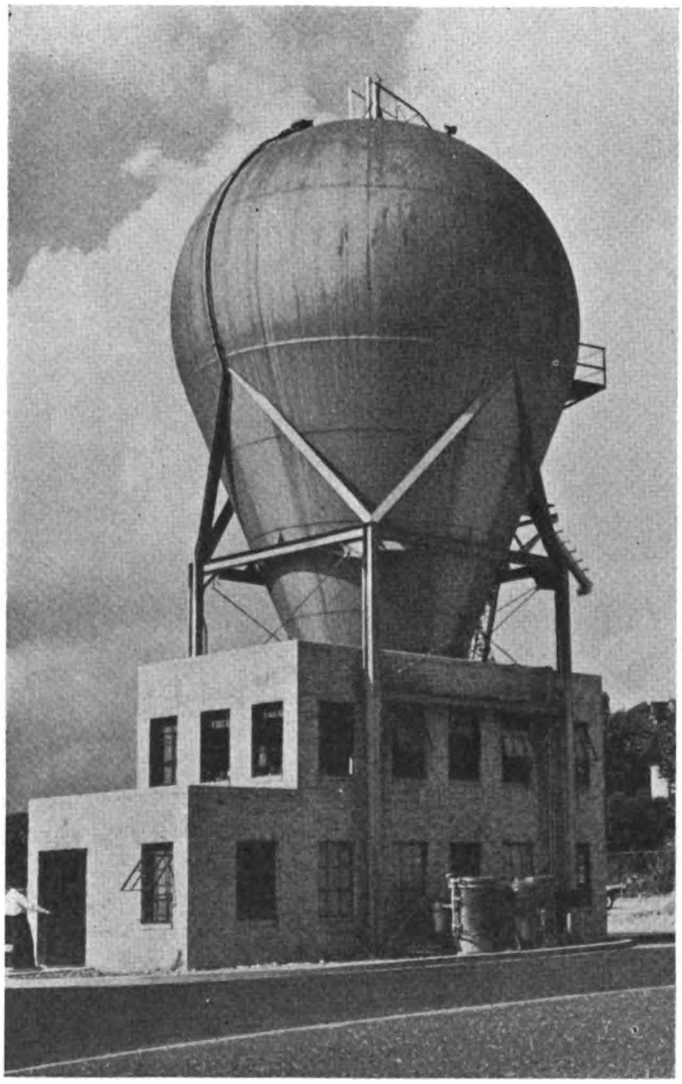


FIGURE 76.—The "Atom Smasher," Westinghouse Research Laboratory, East Pittsburgh, Pennsylvania

the neutrons can be used to disintegrate more uranium atoms, which in turn will give out neutrons, the process will be continuous and the heat produced may be used as a source of power. The only question is whether enough neutrons can be produced to keep the reaction going continuously. The evidence here is not yet conclusive, and while it looks as if there are not quite enough neutrons produced to obtain power, it is possible that such power could be obtained by the splitting of other atoms. Thus, while a few years ago, the question of the obtaining of power from the energy bound up in the atoms was only discussed speculatively in popular scientific magazines, it has now become a very important practical question to the physicist. It has been calculated that if a method of this kind can be worked out, it will be possible to obtain power at a considerably lower cost than it is now obtained from coal.

Study of the Solid State

The physicist has also been busy studying the outer structure of atoms. By means of the spectroscope he has been able to identify many atoms by the color of the light they emit. Using this color he can in turn discover the number of electrons and their arrangement in the outer structure of the atoms. Until recently his knowledge was restricted to atoms which were widely separated as in gases. Calculations have now been made to determine the forces that act between atoms and thus hold them together in solids. Such calculations have allowed the elastic properties, the density, and the heats of vaporization of very simple metals

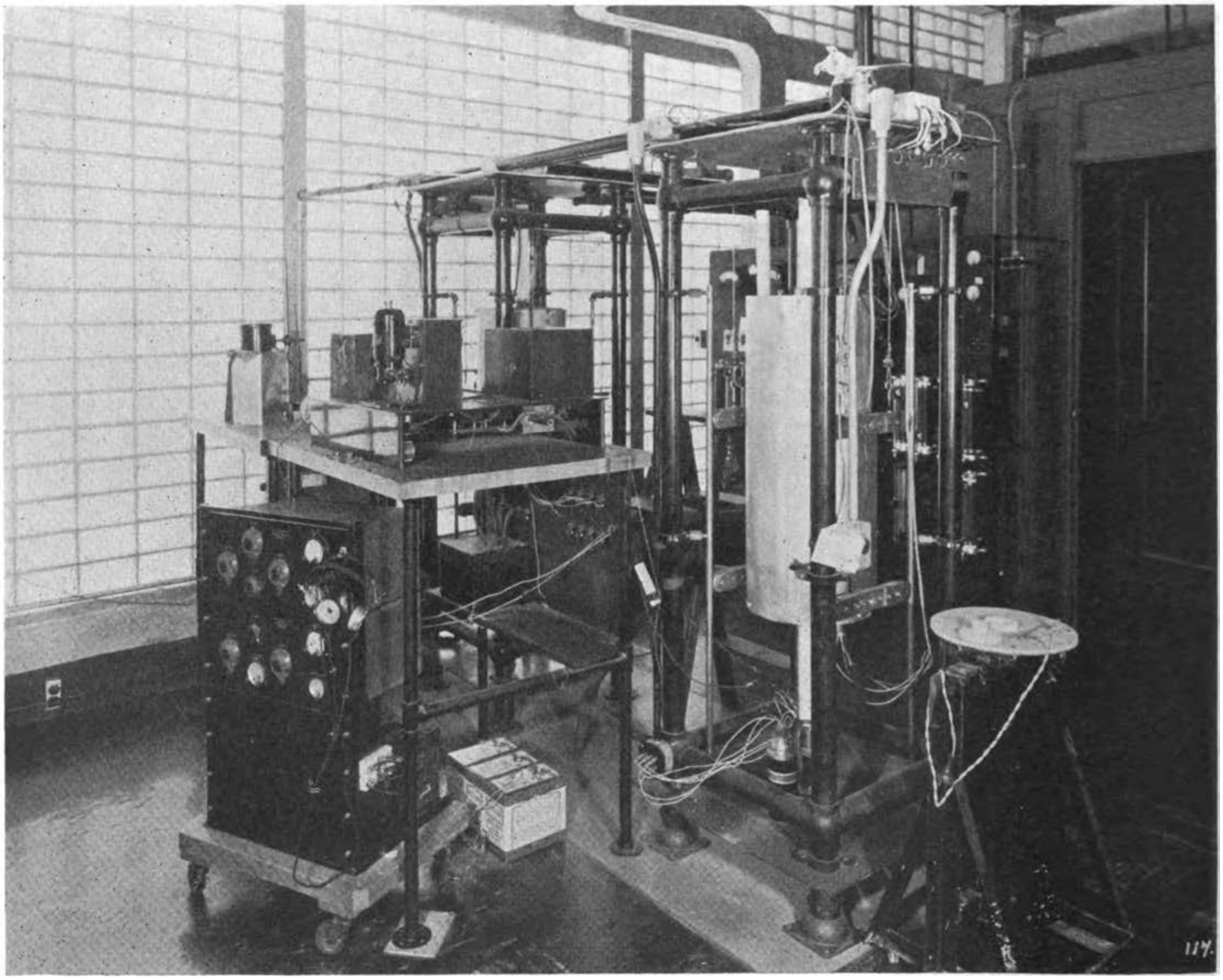


Figure 77.—Viscosimeter for Determination of the Absolute Viscosity of Glass, Owens-Illinois Glass Company, Toledo, Ohio

like sodium and potassium to be calculated theoretically in good agreement with the experimental values. Of course, such metals are not of great practical use, but the physicist has also used X-rays to determine the crystal structure of the metals actually utilized in practice. While complete calculation of the atomic properties of these rather complicated metals has not yet been worked out, there is no question but that in a few years it will be possible to calculate many of the properties of such metals as copper and iron as well as of sodium and potassium. An intensive study of the physical properties of many of the useful metals, and particularly of their alloys, has led to the discovery that there is an internal order in atoms besides the ordinary crystal structure, which has a great deal to do with the physical properties of the alloys. The physicist is even beginning to discuss such questions as the diffusion of atoms in metals, strain and age hardness, and other properties that formerly were considered to be entirely within the realm of metallurgy. By bringing together the knowledge of individual atoms and the forces acting between them with that of the large scale properties of metals such as hardness, tensile strength, etc., the physicist hopes to provide a scientific basis for solving many of the problems now existing in the field of metallurgy. It is to be hoped that in the future the physicist may be able to predict properties of alloys, particularly from his knowledge of the structure of their atoms.

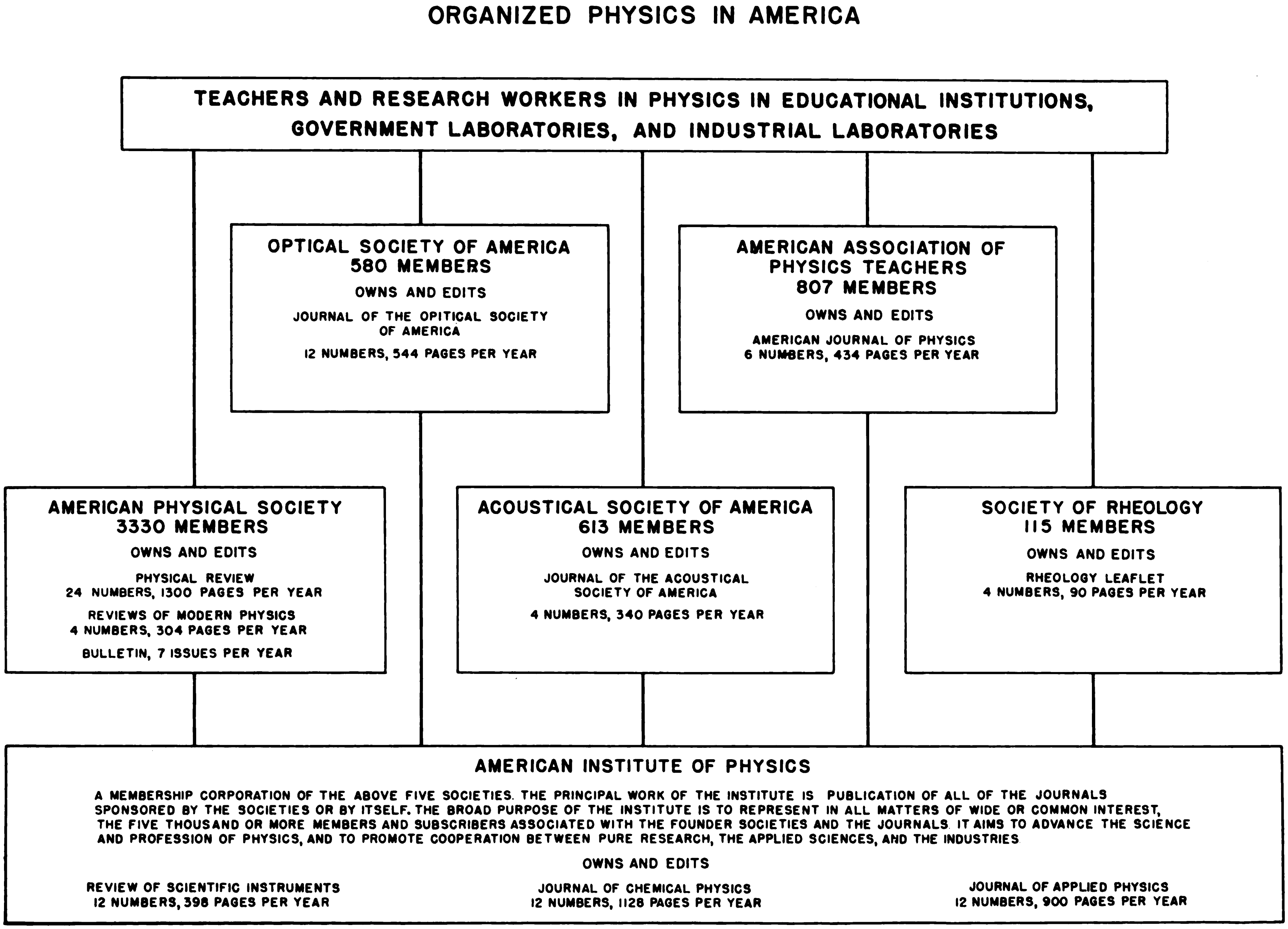
Solar Energy

An extremely attractive field of research is the better utilization of the energy of the sun. It has been shown that we receive on the earth from the sun about 200,000 times as much energy per day as we are now using from all sources. If a small fraction of the energy thus received every day from the sun could be turned to useful purposes, an enormous increase in the wealth of the world would occur. The standard of living which can perhaps be measured in terms of the power available per individual would be greatly increased at no one's expense. With this in mind large grants of money have been given to two institutions to carry on research in the further utilization of this tremendous source of energy. There are several ways in which a greater utilization of this energy might take place. For instance, if it were possible efficiently and economically to carry out in the laboratory the synthesis of compounds carried on every day by plant life with the aid of chlorophyll and the sun, a source of energy would be available. One might perhaps, merely by exposing a particular kind of storage battery to light, produce a chemical reaction which would charge the battery. If that could be done, a very convenient source of power would be available. We have all seen small photographic exposure meters which when pointed toward the sun, indicate the intensity of the current that is passing. By investigation of suitable metals, would it perhaps be possible to make such photocells on a large scale and to obtain large currents that would be useful as sources of power? Still another example in which current is obtained is the thermocouple, in which a temperature difference between two metallic junctions produces a feeble current. Unfortunately the temperature rise produced by the sun is not large enough to give us large currents from a thermocouple. Perhaps, however, if different metals or new alloys were used in making the thermocouple, larger currents could be obtained. All of these processes need further research before anything definite can be said. Even the direct concentration of sunlight by mirrors needs further research before it can be said definitely that, in the future, houses will not be heated or cooled by sunlight rather than by gas or electricity. Research such as this, from which results probably cannot be expected for a long period of time, is best carried on in the universities and in governmental and privately endowed laboratories, but it is quite likely eventually to provide new industries.

Physics Contributes Indirectly to Progress

In the foregoing discussion the direct results of the application of physics in industry have been stressed. There are, however, many indirect effects which, though important, remain intangible. For instance, the existence of a research laboratory in an industrial plant has a stimulating effect upon the mental attitude of the entire industrial organization. The interest of the individual in the plant is broadened and extended beyond his daily task. He begins to make suggestions for improvements in design and technique. The physicist, with his knowledge of fundamental principles, can often be of service in directing these suggestions along promising lines.

Perhaps the most important indirect result of the application of science in industry is the increased faith aroused in the mind of the industrialist in the fact that nature is orderly and that natural phenomena take place according to definite rules which are known, or may be learned, if research be undertaken. The taking of adequate data under controlled conditions, the analysis of these data, and the final drawing of conclusions without prejudice, which is characteristic of the work of a true scientist, gradually have their effect on the thinking of those with whom the scientist is associated. A discipline is established which influences the attitudes of others not only toward laboratory problems but toward shop problems and any other difficulties that may arise. As a result of this change in attitude many of those problems which "can't be solved" have been



A MEMBERSHIP CORPORATION OF THE ABOVE FIVE SOCIETIES. THE PRINCIPAL WORK OF THE INSTITUTE IS PUBLICATION OF ALL OF THE JOURNALS SPONSORED BY THE SOCIETIES OR BY ITSELF. THE BROAD PURPOSE OF THE INSTITUTE IS TO REPRESENT IN ALL MATTERS OF WIDE OR COMMON INTEREST, THE FIVE THOUSAND OR MORE MEMBERS AND SUBSCRIBERS ASSOCIATED WITH THE FOUNDER SOCIETIES AND THE JOURNALS. IT AIMS TO ADVANCE THE SCIENCE AND PROFESSION OF PHYSICS, AND TO PROMOTE COOPERATION BETWEEN PURE RESEARCH, THE APPLIED SCIENCES, AND THE INDUSTRIES.

FIGURE 78.—Organized Physics in America

solved. The realization that there is a vast amount of information which may be used, and the experience that when such information is made available solutions are developed, inevitably stimulates an optimism about the possibility of mastering industrial problems and overcoming obstacles generally.

It is believed that in the above presentation it has been shown that the quotation used at the beginning is not an overstatement. The broad basis in facts and principles, in technology and instrumentation, on which industry is built is predominantly physics and it follows that physical research in industry is one of our most important and most valuable national resources.

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SECTION VI

3. THE ROLE OF THE BIOLOGIST IN INDUSTRY

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ABSTRACT

Biological science has made rapid strides during the last 30 years, largely due to the impact of the ever-expanding physical sciences. To attempt in a brief summary to point out isolated significant influences which have contributed to the development and the technique of industry is certain to confuse rather than to add to our understanding of the place of biology in the modern world, and especially in modern industry. Rather we must emphasize the contributions of a few fundamental generalizations relying on the proper orientation of certain basic concepts common to all science to give us an insight into the scientific methods which have made the highly technical industries of today possible.

The scope of this work can be determined by a study of the Table of Contents of the report of biology in industry. A general discussion of the place of biology in science and industry and the work which the biologist can do are given. Some of the most significant industrial applications are briefly discussed. Special attention is given to the food industries and to certain fields such as the fermentation industries, fats, oils, etc. Nutritional requirements of man and animals from the point of view of the newer knowledge are considered. Biological products, hormones, vaccines, enzymes, vitamins, receive attention, but one must admit not in the proportion which their great importance merits. Chemical products, chemotherapy, fungicides, etc., and parasitology, waste disposal, plant and animal breeding, are considered briefly, and from these vast fields a few outstanding contributions are listed.

The important work of training the biologist, which lies largely in the hands of the universities and the colleges, would merit comprehensive study, but no extensive effort was made to analyze this situation. However, it is pointed out that constant remodeling of the work of the university is necessary in view of the growth of scientific knowledge, in order to meet the changing needs of industry.

Trends in biology are significant insofar as they indicate the influence which great scientific leaders and great discoveries and developments in the physical sciences have had on the biological sciences. Future development will naturally be dependent on the progress of those sciences which supply biology with special techniques, but biology is developing within itself a body of knowledge that will lead to important discoveries.

Introduction

Since prehistoric times biological processes have played an important part in the growth of civilization, but until recently all developments were chance occurrences, and rule-of-thumb methods controlled industrial procedures. Beginning with Linnaeus in the early eighteenth century, the classification and integration of biological knowledge have fairly revolutionized our industrial biological economy. This systematization of information regarding biology has proceeded apace in four main directions. First, we have developed the concept of organization, embodying the wide aspect of organic evolution; second, we have studied structure, morphology, and histology; third, has emerged the idea of function, physiology; and fourth and most recently, we have attacked the problem of mechanism, genetics, biochemistry, and related phases.

Application of science in the fields of nutrition, medicine, agriculture, and manufacturing has lifted civilized man from a creature of circumstance to a position of dominant control of the physical aspects of his environment. Pasteur's biological experiments, based on the best scientific chemical and physical knowledge of the time, led the way for the control and practical suppression of the epidemics and pestilences which had harried mankind for so long. Establishment of his concepts of the nature of life has facilitated the rise of our great food preservation, processing and storage industries, banishing the ancient spectre of famine from the scene of any nation which will intelligently apply them. Recognition of the vitamins and hormones as instruments used in the mechanics of growth and life processes promises to raise the physical activities of a population to a degree of efficiency never before conceived.

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*Appreciation is expressed to Dr. Q. Landis, of the Fleischmann staff, for his assistance.

As the individual who is to develop and guide industrial applications of this stupendous body of knowledge, the modern biologist can no longer afford merely to chase butterflies or dig for worms. The heretofore mysterious and occult life processes are now shown to abide by the fundamental laws of physics and chemistry. But the arrangement and interaction of components within the cell, of cells within the organism, of individuals within a society superimposes upon physical and chemical phenomena a new and profoundly effective factor; that which we call organization. Not only must the modern biologist, whom for our purposes we might call a "biological engineer," be thoroughly familiar with physics and chemistry and their language, mathematics, but he must also have some comprehension of the possibilities inherent in organization. Biologists find it difficult to qualify in all these respects, consequently modern industrial biological laboratories usually represent several classes of training—chemists, physicists, bacteriologists, endocrinologists, etc., cooperating as best they may in the work of the industry.

The revolutionary ideas arising from Wöhler's synthesis of urea released a flood of biological investigations. The controversy between Liebig and Pasteur, the syntheses accomplished by Emil Fischer, the contributions made by Lamarck, Darwin, and Mendel, and the recent spectacular researches of Warburg and other contemporaries on the structure and function of the enzymes comprise a background representing the modern biologist's point of view. Without this background the biologist would be hampered severely in his work.

The biologist never has a simple system, since his most important object of study, the living form, is most complex. At first thought, it might be said that the single-celled organism, e. g., a yeast cell, is a simple structure. Quite the opposite is true; it must possess within one cell all the potentialities of a complete organism; and hence is more complex functionally, and often structurally, than any individual cell of a "higher" (i. e., more complex) plant or animal Living matter cannot be perfectly controlled; hence the perfect experiment is impossible in biology. Many trials must be made, and often statistics must be invoked to aid in the interpretation of results. The chemist and physicist find it hard to appreciate the difficulties of biological research. The engineer may design a plant perfect in construction which fails in operation because he failed to consider, or science did not have available, the precise knowledge necessary to control production.

This report has been prepared from the information supplied by research directors of a number of industrial laboratories and university men interested in biology. It is hoped that it will point out some of the things that biologists can do for industry. If it appears that the biological investigations lag behind those in other divisions of the natural sciences, it is because biology deals with phenomena which are complicated, variable, and not easily susceptible of experimental manipulation. The investigator must be familiar with the biological system which he is attempting to study—the condition of the living thing. It is clear that certain biological experiments require not only knowledge of physics and chemistry but also a knowledge of the normal living organism, the "biological system." If there is a unique biological viewpoint it is associated with an understanding of this relationship and the possibilities inherent in organization.

Industrial Applications

Industries vary greatly in the extent to which they utilize biological research. The manufacture of vaccines, antitoxins, and many pharmaceuticals involves the most meticulous biological control. At the other extreme we have the metallurgical industries where the biologist is concerned only with employee welfare or waste disposal. In any event we may define the industrial biologist from the standpoint of this report as one engaged in research on biological material regardless of his previous training. According to the figures obtained by questionnaires, there are about 1,000 biologists engaged in industrial research in the United States, but under the above classification a much larger number would be included.

It usually requires the cooperation of many scientifically trained investigators to place a product on the market. The sources of raw materials must be carefully investigated. Their cost and uniformity and the economics of bringing them to the factory door are matters of prime importance. Once the laboratory has developed a product and controls satisfactorily its uniformity, flavor, color, consistency, therapeutic or nutritive value, and other properties, the cost of elaboration, methods of packaging, distribution, keeping quality, and superiority over competitive products must be considered as important factors. When the product is ready for market a consumer preference test is necessary. Ways of utilizing waste products must be developed as these may become important sources of revenue in reducing the over-all processing cost. The knowledge of the "biological engineer" is of great value in the consideration of these problems. The biologist will also be consulted in the labeling and advertising of all foods and drugs in accordance with the regulations of the Food and Drug Administration (Federal Security Agency) and of the Federal Trade Commission. Modern advertising and labeling of such products must also be coordinated with the Federal and State regulatory laws. This immense task requires training and experience in legal as well as scientific fields.

We shall pass over with brief mention those industries directly concerned with medicine. The development of chemotherapeutic agents such as sulfanilamide is largely the result of intensive study in industrial laboratories as well as in endowed medical laboratories. Research on the endocrines has led to the commercial exploitation of the hormones. Isolation and study of the viruses may lead soon to developments of industrial significance.

In agriculture the application of the principles of genetics and physiology has led to an astonishing increase in quality and productivity. Not only have plant and animal strains been developed for specific purposes and adaptable to specific environments—resistant or immune to certain diseases—but in many instances the ability of these strains to utilize more effectively the potentialities of the environment in providing food and clothing for men have been raised to a high degree of efficiency. Knowledge of soil and climatic conditions has made its contribution to this advance, as has research by plant pathologists, geneticists, biochemists, bacteriologists, entomologists, and workers in other fields. Some of this research was unorganized, some was due to industrial organizations, while probably the most has come from the State supported agricultural experiment stations.

The field of nutrition has undergone a near revolution. Newer knowledge of the mechanism of biological processes, the function of the vitamins, the importance of minerals, and studies of energy transformations, immensely accelerated by the use of radioactive and isotopic "tracer" atoms within the animal body in relation to the foods utilized has had great industrial repercussions. This has also indirectly influenced agriculture; studies in animal husbandry and nutrition have shown how to feed for lean meat, for egg production, and even for better wool and fur. Although research in this field was initiated mainly in the universities a rapidly increasing amount is being done in strictly industrial laboratories, while nearly an equal amount in the colleges is now being subsidized by industry.

Transportation and storage become big problems in the economy of civilized man, and in most cases some processing to improve characteristics of the product and prevent deterioration is necessary after harvesting, whether the crop be plants, animals, or micro-organisms. During processing the cells and structure of the product may be changed, and appearance, digestibility, flavor, odor, tenderness, etc., be favorably or unfavorably influenced, but the control measures of the biologist and his other scientific collaborators should be available. Ripening processes involve enzymic changes, and it is necessary to control these changes in the product due to its own enzymes or to those of invading micro-organisms. The battle between the biologist and the spoilage micro-organisms is a continuous one, and the outcome is dependent upon the information furnished by biological research. It is in the preservation of foods that the research biologist has made some of his most important contributions. The biologist is also concerned in keeping out, killing, or removing disease-producing organisms, both infectious and those producing toxins. A great deal of the research in this field is due to industrial organizations.

The Food Industries

The food industries have, in general, been slower to use biologists and their discoveries than have some other industries; this is probably due to their firm anchorage in the methods of antiquity. A few of the biological sciences, however, are well represented in some of the food industries at present. Bacteriologists, for example, are considered necessary collaborators in research on milk products, meats, and canning. Researches in relation to the adulteration of foods and drugs have been carried on intensively by chemists and bacteriologists. There exists, however, a real need for more emphasis on investigations of the histology of useful plants. Food microscopy, as it is called, is a

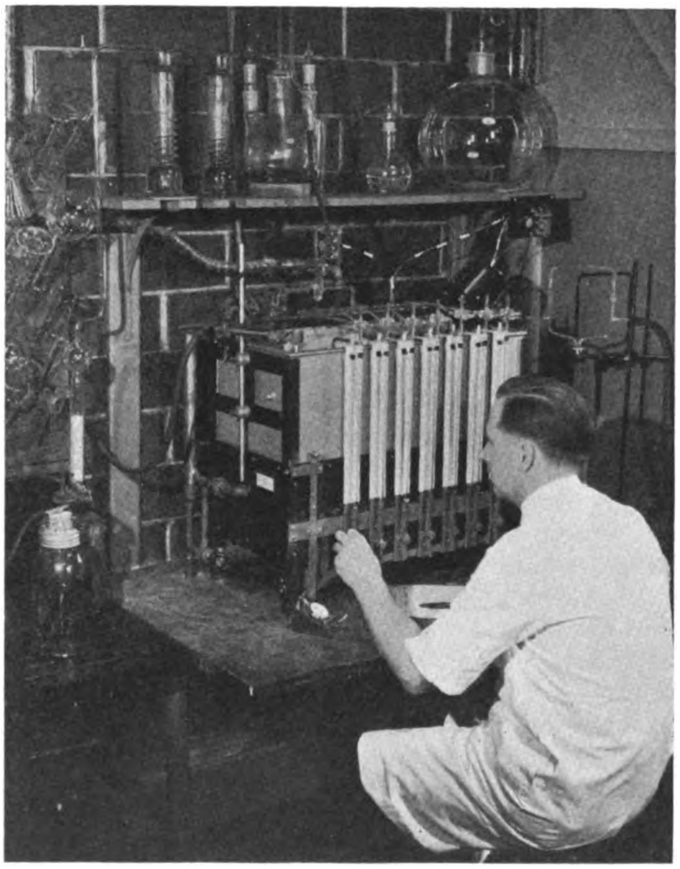

FIGURE 79.—Studying Oxidation-Reduction Systems, Fleischmann Laboratories, New York, New York

neglected field. Especially neglected have been studies relative to the structure of the seed kernel. In the following discussion of the problems in connection with some of the more important food industries, a few examples of the use of biologists in research will be cited and their more extensive use suggested.

Meat and meat products.—Studies of the growth, breeding, and nutrition of meat animals obviously involve research by many kinds of biologists. Then from the time the animal is killed until its meat is consumed there is work for biologist and chemist in determining methods for reducing to a minimum undesirable chemical and physical changes and encouraging desirable changes. Recent studies by bacteriologists on the amount and kind of contamination by micro-organisms at different stages during the handling of meat in the packing plant have shown the importance of further research. The growth of micro-organisms and consequent spoilage of meat is an ever-present problem to be solved. The biologist must investigate not only changes due to micro-organisms, but also those due to enzymes of the meat or to purely chemical reactions. Thus the chilling of meat or freezing by either quick or slow methods brings problems to the biologist, who must be trained in anatomy, histology, and microscopy as well as in biophysics and biochemistry. The biologist encounters special problems in changes in taste or odor and in loss of "bloom" and other changes in pigmentation including discolorations. The oxidation of fats, use of antioxidants, and the causes of rancidity still present many problems. Investigation is needed on ripening and "tenderizing" meats and on their nutritive value.

Preservation of meat and meat products by heat presents the biologist with problems. While the processing of canned meats by the usual steam-pressure-cooker methods still deserves study, less adequately explored is the field of processing certain canned meat products such as luncheon meats or hams so that only part of the micro-organisms present will be killed, yet the product will keep for a reasonable time at low storage temperatures.

Curing, pickling, smoking, and drying of meats are being investigated. The bacteriology of the brine used in curing hams and bacon needs study to enable better control of the curing process. This may lead to the use of pure cultures, an example of which is the addition of cultures of lactobacilli to a certain tangy sausage with consequent improvement in the quality of the product.

Fish and sea foods.—In general the sea-food industry faces problems similar to those of the meat industry. An important difference, however, is the fact that fish and other sea foods usually are not grown but must be sought where they grow in nature (an exception is, of course, the breeding of game fish and planting of lakes and streams primarily for the sake of the sportsman). Nevertheless, the ichthyologist, limnologist, and biochemist are carrying on research of benefit to the commercial fisherman. Two interesting examples of this aid are: A study of the habits of fish to guide the fisherman to the best places to net fish; a study of the organic matter content of the water, or rather its availability; this can be measured by determining the rate of bacterial multiplication and the rate of oxygen absorption in the water due to bacterial action. The case of decomposition of fish (and other sea foods) both by autolysis and by microbial action, and the fact that fishes usually are harvested at some distance from the place of processing, have given the biologist especially difficult problems.

Milk and milk products.—While milk may not be considered an industrial product when first produced, it becomes one as soon as it reaches the market-milk plant, the cheese factory, condensery, or other processing plant. The dairy industry is making more use of biologists than are some of the other food industries. Bacteriologists and biochemists in particular are doing research on milk and milk products, especially on aspects of sanitation, preservation, nutritive properties, and utilization of byproducts.

Milk is subject to contamination by micro-organisms which may grow and cause spoilage, as well as by pathogenic bacteria. Because the delicate flavor of milk and certain of its physical characteristics are so readily changed by some of the commonly used methods of food preservation like heat and freezing, its preservation presents problems different from those encountered in most foods. Asepsis, cooling, and pasteurization are commonly employed, but use of pressure, sound waves, ultraviolet rays, etc., is being studied. Sanitary control is not only of interest to the market milk industry but also to the ice cream industry, because of the increasing stringency of laws concerning the bacterial content, more especially that of *Escherichia coli*, in ice cream. The butter industry is faced with problems concerning the original cream as well as the butter which has been in cold storage for months. The biologist is of assistance in the investigation of the harmful processes which may take place. Evaporated milk presents problems especially to the biochemist interested in the coagulability of the casein as influenced by composition of the milk. Both the nutrition expert and the bacteriologist find unsolved problems concerning the proper processing of the canned product.

Fermented milk products are manufactured partly as a means of preservation of milk, but primarily for their inherent characteristics. Fermented milk drinks (buttermilks) are, for the most part, prepared with more than one species of micro-organism, and the resulting mixed fermentation presents special problems. Cheese making usually involves the activity of still more species of micro-organisms and presents problems of even greater complexity. The bacteriology, physical chemistry, and biochemistry of most of the hundreds of kinds of cheese are still not clear, and an enormous amount of research will be necessary before the cheese maker can manufacture consistently a product of the highest quality.

Nutritional studies on milk and milk products are assuming increasing importance. Vitamin and mineral content, change of alpha lactose to the beta form, production of soft-curd milk, irradiation of milk, activation and feeding of yeast to cows to increase the vitamin D content of their milk, and the effect of the form of lactic acid upon assimilation are all subjects of present interest and research.

Eggs.—Stored eggs are subject not only to spoilage by micro-organisms but also to deterioration due to their own enzymes. The industry is interested in improvements over the usual chilling or "cold-storage" preservation; these include oiling of the shell, with or without replacement of the air in the egg with carbon dioxide, and storage in an atmosphere with a controlled content of carbon dioxide or ozone. The freezing and drying of eggs also present unsolved problems; for instance the drying of egg white by the usual methods used for milk injures the whipping quality.

Fruits.—It is evident that various biologists would be concerned in research on fruit production, and large producers are employing biologists to assure greater yields and improved quality. The transportation and storage of fruits present difficulties that differ in some respects from those encountered with animal products. In most fruits and vegetables the cells remain alive long after harvesting and continue respiration and other functions. Most fruits reach a certain stage of ripeness or maturity desired by the consumer and must be marketed at that stage. For these reasons the time of harvesting, the methods of handling, the use of artificial agents or specific chemicals such as ethylene for increasing the speed of ripening, are all of great importance and are the subject of considerable research by biologists. Prevention of mold and bacterial growth is also an important problem. The optimum temperature of storage varies with the fruit to be stored and temperatures that are but slightly too high or too low may ruin the product. Investigations on this subject by plant physiologists and biochemists continue, but these researches now are concerned chiefly with a study of controlled atmospheres about the fruits, with special attention to concentrations and proportions of oxygen

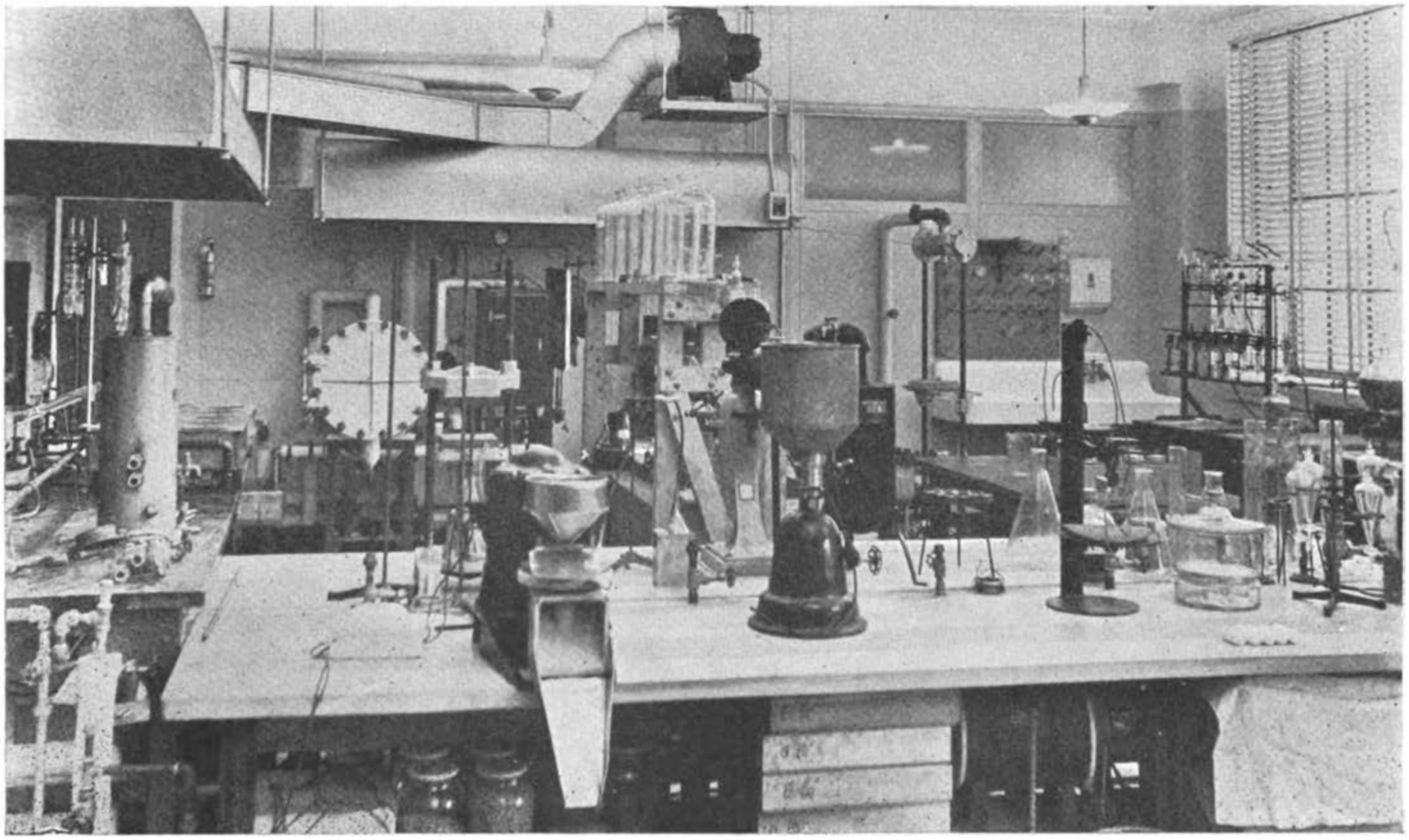

FIGURE 80.—Corner of Food Technology Laboratory, General Foods Corporation, Hoboken, New Jersey

and carbon dioxide, and to the use of ozone. Investigations on the method of extracting and preserving fruit flavors for use in gelatin, ice cream, and candy are being carried on in a number of industries.

Freezing of foods is a large and rapidly growing industry. Fruits and vegetables are being frozen chiefly by quick freezing methods, although some fruits are frozen more slowly. Development of quick-freezing methods has opened a large field of research by biologists, for fruits and vegetables suitable for canning are not necessarily adapted to freezing, and old varieties are being tested and new varieties sought. Inactivation of enzymes, especially of those of vegetables, is being investigated, for the enzymes are not destroyed by low temperatures and may cause appreciable changes in the frozen product. The chemical and physical changes which take place between harvesting and thawing of the frozen product before consumption also are receiving the attention of biochemists and biophysicists.

Most fruits are so acid that spoilage of the canned product is not a major problem, although occasionally difficulties arise in the preservation of such fruits by drying. Physical and chemical changes in the plant cells which take place during harvesting, lye treatment, sulfuring, drying, and "sweating" are subjects for research. The treatment of fresh fruits to destroy molds and bacteria may extend the marketing period.

Vegetables.—The problems in connection with the freezing of vegetables have been discussed under the heading "fruits." Biologists have been helpful to the canning industry in its packing of vegetables. The production of vegetables suitable for canning has inspired some important lines of research. A notable example is the discovery that deficiency of soils in boron is responsible for "black heart" in canning beets. Geneticists and plant breeders are engaged in producing new varieties, especially suited to processing and shipping.

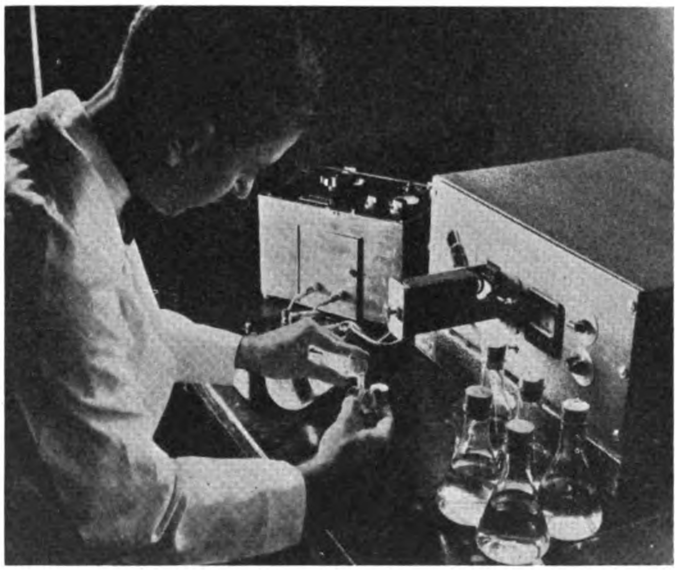

FIGURE 81.—Photoelectric Colorimeter for Measuring Amount of Vitamin A in Foods, Purina Mills, St. Louis, Missouri

The canner is always torn between the desire to heat the canned product as little as practicable, so as to avoid harm to the quality of his product, and to administer a severe heat treatment to assure the inactivation of all spoilage organisms. The bacteriologist has studied the heat resistance of spoilage bacteria, the sources of these organisms, and new methods of processing. He is at present interested in the development of the new high-temperature short-time methods.

Fungi.—The cultivation of mushrooms, molds, yeasts, and bacteria for use as foods is a large industry in itself with many possibilities as yet unexplored. The industry in the United States produces annually about 18 million pounds of mushrooms. This is a good illustration of how sound biological methods make possible great industries. The rapid growth of the mushroom industry is mainly due to two biological processes, the development of pure culture methods of growing spawn and improvement in the preparation of compost humus.

Commercial yeast manufacture.—The cultivation of yeasts for food, for various vitamins or vitamin precursors, for leavening of bread dough, for manufacture of beer, wines and other foods and beverages has been the basis of research by the biologists who are still studying the physiological characteristics of yeasts and efficient methods for their cultivation. Studies in this field have thrown light on the chemical and physiological processes in higher plants and animals.

Manufacture of bacterial cultures.—Many food industries use pure cultures of bacteria and the preparation of these cultures is a considerable industry in itself. In the dairy industries starter cultures are needed for the manufacture of cheese, butter, and fermented milks. The production of special enzymes not only from bacteria but also from yeasts and molds for use in food and other industries is increasing in importance. The successful growth of leguminous crops such as alfalfa, clover, peas, and soybeans, often depends upon the use of suitable cultures of the nodule-forming organisms—the symbiotic rhizobia. Obviously the bacteriologist finds research necessary to determine methods for the preparation of effective, long-lived cultures which are able to perform the functions expected of them. The growth of cultures for the production of enzymes introduces problems not only of yield but of isolation and purification of the product. It is anticipated that research work on enzyme products will continue to grow in importance.

Cereals and cereal products.—The cereal industries are faced with problems in grain production, processing, nutritive properties, and spoilage. Only during the past 10 years has the extensive use of combine harvesting so changed the biological character of wheat as to impose difficult problems for the milling industry in enzymic control. Often problems of flavor control are associated intimately with biological effects.

In the baking industry, for example, ropiness of bread and spoilage by molds continue to cause trouble. Recently it has been found that the salts of acetic and propionic acid are valuable in the prevention of molds on bread. The physical properties of the finished bread continue to be investigated and improvements in flavor are being sought. The weevil hazard is one to which all makers of meals, cereals, and crackers must attend. The number of breakfast foods has multiplied greatly in recent years and the efforts continually being made to improve their flavor and dietetic value, as well as vitamin and mineral content, demand careful biological testing. Recently the restoration of vitamin B_1 to white bread by means of special milling processes, the addition of thiamin, or the use of high B_1 yeast have been the subjects of intensive research.

Sugar and sugar products.—Although the microbial content of sugars for canning now is being controlled in a fairly satisfactory manner, thanks to past research, there is still room for improvement. Occasional lots contain large enough numbers of spores of thermophilic, anaerobic bacteria to make them unsuitable for use by the canner. The need for further research and continuous control of manufacturing methods is indicated. Spoilage of honey, sirups, and candies also needs further study.

Food fats and oils.—The nutritive value, causes of deterioration and methods of preservation of fats and oils are subjects for further study by biologists. The influence of various catalysts on oxidative changes in fats and oils brings about changes in flavor. Microorganisms, especially molds, have been shown to be responsible for both oxidative and hydrolytic changes.

Spices, condiments, and unfermented beverages.—The antiseptic and germicidal power of spices and condiments, and their preservation and use for the control of the bacterial content of foods continue to be subjects for research. Biologists find subjects for research in

Figure 82.—Corner of Research Laboratory, Swift and Company, Chicago, Illinois

the removal of the coffee "bean" from outer skins and pulp and a possibly controlled fermentation of the coffee bean to improve flavor and aroma. Likewise, the removal of cocoa beans from pod and pulp and the accompanying fermentation are being studied, as is the "fermentation" of tea leaves. Important studies on the staling of coffee have recently appeared.

Fermented foods.—The biologist is essential to industries which manufacture fermented foods like sauerkraut, pickles, olives, fermented milks, vinegar, and beverages such as beer, and wines. Bacteriologists and biochemists have developed satisfactory methods for the preparation of sauerkraut and have investigated the bacterial flora and causes of spoilage. Similar work on cucumber pickles and olives is occupying the attention of biologists in these industries. Although the manufacture of vinegar by fermentation has been carried on for centuries, methods of production have recently been so greatly improved as to be almost completely revolutionized.

In fermentation industries like brewing and wine making, the yeasts used are studied for food requirements, methods of propagation, maintenance of desired characteristics, and possible improvement of their activity. The aging of the products, maintenance or improvement of their quality, and prevention of spoilage also are being investigated.

A recent development of great importance to the food industry is the development of a yeast containing 10 to 20 times as much vitamin B_1 as that of ordinary beer or baker's yeast. The development of special strains of yeast and methods of growing for the production of ergosterol and riboflavin are examples of research in this field. A special yeast high in invertase activity has also been recently developed.

Fermentation Industries

It has been estimated that the present annual production of fermented products and chemicals produced by fermentation is about as follows:

Malt liquors, 1,669 million gallons.
Wines and spirits, 145 million gallons.
Industrial alcohol, 152 million gallons.
Acetone (including synthetic) and butyl alcohol, 150 million pounds.
Lactic acid, 1,292,000 pounds edible and 5–7 million pounds, technical.
Citric acid, 15 million pounds.
Gluconic acid, 500,000 pounds.
Sorbose, 100,000 pounds.

New organisms.—In the highly competitive fermentation industries there is a constant pressure for improvement of the processes, as witness the numerous patents. While it is not possible to patent an existing micro-organism as such, it is considered a point of novelty and a patentable feature if one has developed an organism having characteristics commercially significant. If a company is not to be the prey of any inventor who comes to offer a new organism, it should itself explore the possibilities of isolation and testing of new organisms. Some large companies recognize this and have in their employ trained bacteriologists or mycologists.

Changing economic conditions may so affect the availability or price of the raw carbohydrate for the fermentation as to cause a change in desirability of an organism for a given fermentation. For example, in the early years of butyl fermentation, the Weizmann organism held the field because of its superiority in the production of butyl alcohol and acetone from corn. Some 10 years ago molasses displaced corn, and immediately butyl organisms of a new type were in demand. Their discovery was an assignment for the microbiologist, and to his credit may it be said that by deliberate selection from many new isolations of butyl bacteria he found new species and particular strains far superior to the original commercial butyl types. A spectacular current development is a new technique for the controlled adaptation of micro-organisms.

Nutritional requirements.—It is obvious that to grow bacteria and yeast one must supply the proper food. Unfortunately all the factors involved in the growing process are not known even by the best informed. The gross energy-yielding nutrients are known but the requirements for optimum functioning are but imperfectly understood. It is becoming increasingly evident that bacteria and even higher plants require vitamins just as much as do higher animals. In nature micro-organisms may obtain these substances from one another or from other plant and animal materials. In industrial operations the micro-organism is shut off from associated organisms and must depend upon the food supply offered or upon its own synthetic powers. By and large, shotgun methods of supplying these feeds are employed, such as use of extracts of natural materials in the fermentation mashes. When it is not known what growth factors are required, it is impossible to determine except by trial and error experimentation whether or not the factor needed is present in the extract. In microbiology the necessity for growth factors has long been appreciated. Because of recent developments in animal nutrition, advance in the knowledge of the nutrition of micro-organisms has been accelerated.

Physical factors.—Consideration must be given also to such factors as optimum temperature, hydrogen-ion concentration, and oxidation-reduction potential. Means of control of these factors are well known to the biologist but their need is frequently not recognized by plant operators.

Biological Products

Vitamins.—In the last decade the vitamins have moved on from the research laboratory to a place in industry. The developments in the vitamin field are an excellent example of research work leading to the establishment of new industries. It is estimated that the sales value of pharmaceutical vitamin products, such as Viosterol, cod-liver and Haliver oils, amounts, annually, to $125,000,000 in the United States. The value of food products sold on the basis of their vitamin content must amount to many times that of the pharmaceutical products. Milk and cereals which have been treated so as to enhance or restore their vitamin potency are produced in large volume. Oleomargarine fortified with vitamin A is another product featuring the vitamin content as a basis of sale. Most infant foods are now prepared with careful regard for their vitamin content. Many poultry and dog feeds are compounded with a view to insuring an adequate supply of these nutritional elements, and sales are promoted to a considerable degree by the advertising of the vitamin content. The volume of this business is increasing rapidly.

Restoration to food products of various vitamins removed in processing is today one of the outstanding questions under discussion by nutritionists, medical men, and food manufacturers. Although there is no general agreement as to the proper extent of such restoration or fortification or the procedure that will best conserve the public health, there can be no doubt that the tendency is toward increasing the vitamin content of foods.

In the beginning the recognition of the existence of a vitamin was the work of the biologist, or of chemists trained in biology, and all through the stages of purification, isolation, and synthesis the work is guided by biological assay. Without this guidance the chemist would be unable to plan his work or to know the results obtained.

When the interest in, or need for, a vitamin has reached the dimensions of a public demand, the problem becomes one of manufacture. Then the work of the chemist and the engineer becomes of importance. But even here, satisfactory control of the quality of the product must be maintained. Where suitable chemical methods become available, the biological assay gives place to the chemical analysis for vitamin control. The use of micro-organisms in place of rats for assaying vitamin products is a recent development.

Enzymes.—The enzyme rennin has been used in the cheese industry for centuries. However, only relatively recently has the importance of this class of very reactive agents in the chemical processes of the living cell been recognized. Still more recently the possibility of extracting enzymes from the tissues and of using them to cause desired chemical transformations in industry has been attended with considerable success. The number and kinds of enzymes are enormous, and their discovery and application present fields for practically unlimited research.

There are available commercial enzyme preparations such as invertase from yeast, pepsin, rennin, papain, pancreatic extracts, diastatic malt extracts, and microbial proteases and amylases. Other types of enzymes could no doubt be prepared in large quantities if applications were developed.

Two of the well-known commercial uses of enzymes are found in the leather and textile industries. Originally in the tanning industry, the sweating of hides was followed by puering with dog or bird excreta, and in the textile industry desizing of fabrics was done in stagnant water. Following the discovery that the desired reactions are due to specific enzymes, the use of crude mixtures of animal feces was discarded and a standardized enzyme preparation was substituted.

In the food industries, many applications of enzymic properties have been made. Invertase preparations are widely used to produce a noncrystallizable soft cream center for chocolate-coated confections. Invertase is also being used in effecting the partial hydrolysis of sugar syrups. In the meat industry, plant proteases like papain and bromelin have been successfully used to make various meat products tender. On the other hand, some food industries are primarily interested in the inhibition of enzymatic action; for example, quick-frozen foods are first scalded to render the enzymes inert.

Studies of the enzyme systems in citrus fruits have resulted in a process for stabilizing the natural clouding of citrus juice, and there is in use also a process for drying orange pulp for cattle feed which uses enzymic action to increase the capacity of the driers. In the production of pectin from apple pomace, the disturbing presence of starch has been eliminated by the application of fungous amylases. Other fungous preparations containing pectinase have recently been introduced for the clarification of various fruit juice beverages. In the brewing industry, bacterial amylase preparations are in use for the liquefaction of unmalted cereals such as corn and rice. Proteolytic enzymes are used, not only in the early stages of manufacture to render soluble the proteins of the mash, but also in the final clarification of malt beverages by removal of the protein haze.

For the manufacture of various sizing pastes to be used in the paper industry, amylases offer particular advantages because of the various grades of material which can be uniformly produced. Other interesting applications of enzymes include their use to digest the gelatin in the recovery of silver from used photographic films and in the deproteinizing of rubber to produce a highly water-resistant product, as well as the use of pancreas extract for the production of soft-curd milk.

The levels of phosphatase in milk and in blood vary with the degree of infection. The phosphatase test, which depends upon the heat stability of the enzyme, is used in industry to determine whether milk is pasteurized at the correct temperature.

In the first steps of commercial preparation of certain antitoxins, successful use has been made of proteolytic enzymes to digest and in this way to remove contaminating proteins. The successful use of proteolytic enzymes to separate mixtures of hormones also has been carried out.

The industries described above by no means exhaust the commercial uses of enzymes, and it is not too much to predict for the future still more industrial applications. It may be said that these substances are potentially useful to any industry which is concerned with products of a carbohydrate, proteinaceous, or fatty nature.

Hormones and auxins.—Hormones, the secretions of the ductless glands of animals, play a role in embryo development, in the coordination of the secretion of digestive enzymes, in the function of the nervous system (neurohormones), in the control of the metabolism of carbohydrates, fats, and proteins, in growth, and in reproduction. Many of these regulators involved in the control of vital processes in both plants and animals have been isolated in a highly purified form or have been synthesized.

The early recognition that many abnormal and disturbed functions of man and animals are the result of the production of too much or too little of certain endocrine glandular secretions resulted in the development of methods of treatment by the injection or in certain cases the feeding of gland substances. Classical cases are the use of insulin for the treatment of diabetes mellitus, the use of sex hormones to aid in the physiological adjustment (treatment of the symptoms) at the time of the menopause, and the purification of the pituitary hormone used in childbirth. In plant culture, hormone extracts and auxins are used by florists and horticulturists.

The advent of hormones in the treatment of various disorders has made it necessary for the biologist to survey the hormone content of the endocrine glands of various species, and thus to guide the chemist in the selection of the most potent sources of a particular hormone. It is the function of the chemist to isolate, purify, and synthesize these active substances and of the biologist to study their consequences on living organisms.

Vaccines.—Man has learned some of the ways by which one biological form protects itself against the predatory action of another. This knowledge has enabled him to devise ways of aiding the form attacked.

The observations of Jenner made on cowpox led to vaccination as a protective measure against smallpox. The knowledge was not further significant, since it indicated nothing as to the mechanism involved. It remained for Pasteur to make observations on chicken cholera, anthrax, and rabies that did reveal something of the processes concerned and the road to be traveled to reach other goals. The manufacture of vaccines to be used in preventing typhoid fever, cholera, plague, yellow fever, cattle tick (Texas) fever, blackleg, hog cholera, tuberculosis in man and animals, demands a high type of biological service. Research in this field may lead to the prevention of many other diseases of man and animals. Witness the recent development of vaccination for yellow fever and for equine encephalomyelitis, a disease transmissible to man. Without the former our air lines to South America would probably not be permitted to operate. "Jungle yellow fever" in South America now presents a different aspect of an old problem. Recently a peculiar type of malaria brought from Africa by airplanes offers a new problem for control.

Sera.—Protective substances such as antitoxins may be produced with an appropriate stimulus, and these may be used to prevent or cure disease. Antisera for diphtheria, tetanus, anthrax, hog cholera, and other diseases are widely used. The manufacture and standardization of sera demand the most exacting work with the organism used to produce the stimulant, the animal producing the serum, and the animals used to determine the potency of the serum. It is chemical work with reagents from living forms.

Diagnostic agents.—The diagnosis of typhoid fever, of Bang's disease in domestic animals, and of white diarrhea in chicks is made by use of suspensions of the causal organism. Tuberculosis is detected by using a fraction of the cell content of the tubercle bacillus. The eradication of bovine tuberculosis in the United States, now nearly complete, has been accomplished by the destruction of the infected animals as shown by this test. The results of its use in man still show the need of research directed toward the improvement of the product. In each of these fields the selection of the organism and its nutrition are most important, as evidenced by recent work on the selection and cultivation of the particular strain of diptheria bacillus to be used in the preparation of toxins and of the tubercle bacillus in the making of tuberculin. Other examples are the Weil-Felix reaction in the diagnosis of typhus fever and the complement-fixation and other tests for syphilis. Two diseases in which important use is made of the testing of individual susceptibility are the Shick test for diphtheria and the Dick test for scarlet fever. The very latest tools of the physical chemist, the ultracentrifuge, electrophoresis, and diffusion apparatus, are employed in determining the purity and nature of tuberlin. Further biological research is still needed on this product.

Chemical Products

Chemotherapy.—The treatment of disease with chemical substances that selectively destroy the harmful organism without doing serious injury to the animal is the object of numerous researches. The recent discovery of sulfanilamide and its remarkable therapeutic properties, and the still more recent findings of Dubos regarding the products of micro-organisms to be used in the treatment of disease indicate the significance and possibilities of research in this field.

Fungicides, insecticides, germicides, detergents.—The crops of the farmer are constantly being threatened by parasitic plants, smuts, mildews, rusts, and wilts, and by such insects as the grasshopper, the potato beetle, the codling moth; his animals are threatened by various micro-organisms. The building industry must consider the wood-destroying fungi, blue stain fungi, and insects such as termites. The textile industry also must give consideration to the same agencies, for all textiles are exposed to the destructive action of fungi and bacteria, and the textiles made from animal fibers, such as silk and wool, are attacked by clothes moths and other destructive insects. The organic matter produced on the farm is exposed to attacks of varied rodents, as is organic matter in transportation and processing.

The development of products used to protect material against the action of these various destructive forms is an important industry in which the biologist must find a place. The larger producers of these products find it necessary to maintain experimental colonies of the species to the influence of which their products are exposed. In dealing with green plants, there has been developed a method for controlling the growth of weeds by the use of sodium chlorate.

The detergent industry is a very old one. However, it is one in which great progress has been made during recent years. The value of soaps as agents to remove and to inhibit the growth of various micro-organisms has not been recognized. The development of any compound which shall have marked action as a wetting agent has found great use not only in the textile industry but also in the application of fungicides which, without adequate wetting power, cannot be uniformly distributed over the surface of plants on which they are used. The biological role of detergents has not been widely recognized. In the cleansing of all types of food utensils, especially those in which various types of bacteria exist, reliance has been placed on the destruction of the micro-organism by some harmful agent such as heat. In many connections this agency has distinct limitations. It can be partially overcome through the action of effective detergents which will aid in removing protective films of organic matter as well as micro-organisms. There has been rapid development in all of these fields in recent years, but much still remains to be accomplished. The use of dilute solutions of sodium hydrate, trisodium phosphate, and metasilicate in the dairy has aided in the production of milk with low bacterial content.

Relation of parasites to industry.—The harmful effect of parasites on workers in certain countries offers a serious handicap to industry. Investigations have shown that the presence of a hundred or more hookworms exerts a measurable effect on the mental and physical development of an individual. The occurrence of hookworm and malaria in certain sections may become so prevalent that it is advantageous to locate the industrial plants outside these endemic areas. The coffee and tropical-fruit industries must operate in endemic areas of parasites, hence the clear recognition

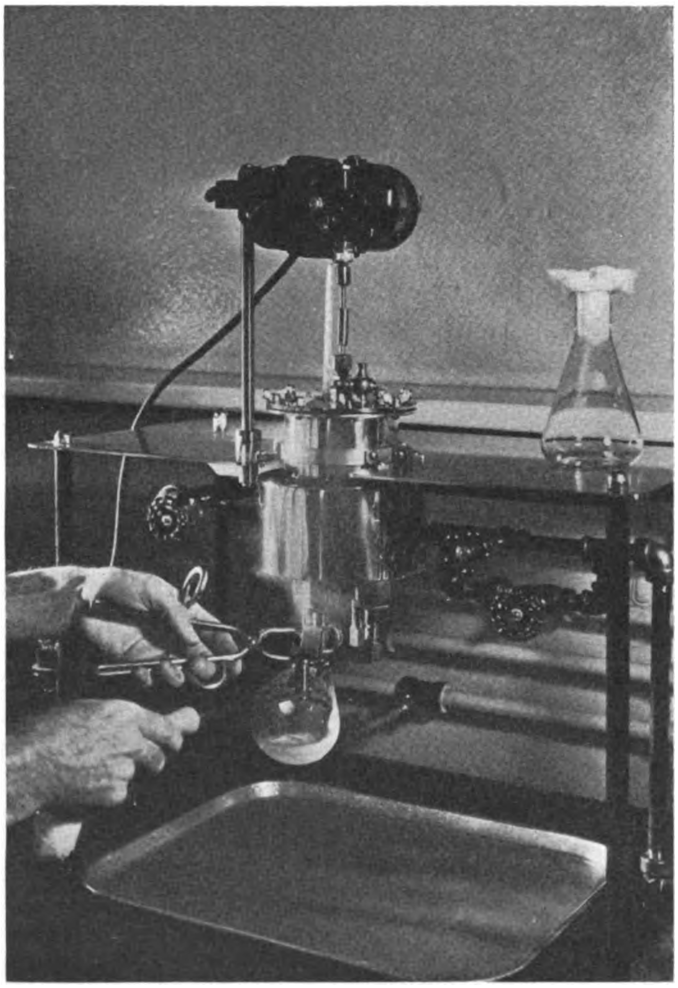

FIGURE 83.—Determination of Thermal Death Time of Micro-organisms, H. J. Heinz Laboratories, Pittsburgh, Pennsylvania

of the great importance of having workers free of parasitic disease.

The relation of parasitology to food industries is well known. Often fish are from lakes harboring the larval forms of *Diphyllobothrium latum*—the fish tapeworm. Fish are intermediate hosts also of various other parasites of man and domestic animals. The development of the fur-farming industry has brought with it the use of fish as feed for foxes, minks, and other animals. This new and widespread use of fish has been accompanied by serious outbreaks of parasitic diseases. Especially is this true where the fish harbor larvae of the trematode, *Troglotrema salmincola*, which carries to dogs a virus disease.

The relation of such a parasite as *Trichinella spiralis* in pork constitutes a major parasitological problem for the meat-packing industry. The presence of human tapeworm cysts in pork and beef (measly pork and beef) is also a constant source of loss and annoyance to the packing industry.

Quite apart from the direct influence on man, the occurrence of parasitic diseases such as cattle tick fever in cattle, stomach worms and liver flukes in sheep, results in great economic loss to the food industries.

Waste Disposal

The wastes of many industries are organic in nature, or at least affect life in the soil or in the water to which these wastes may be added. The disposal of industrial wastes must be accomplished through the use of natural agencies. In many instances these agencies cannot be used in their normal environment, and artificial systems must be developed for the disposal of the particular waste. A system effective in one connection may not operate in another, since the kind of organism concerned will depend upon the nature of the waste; and since the organisms may differ in their demands, the systems must provide varied environments. Thus, the activated-sludge process for the disposal of household sewage and industrial waste should be adapted to each particular problem.

The disposal of industrial wastes must be accomplished without endangering the health of man or his food supply. The disposal must also be carried on under such conditions that the area in which it is taking place is not made less attractive for man.

The loss of fertilizing value connected with the older systems of waste disposal was great. The newer systems seek to leave some part of the organic matter in such form that it can be returned to the land to aid in maintaining the farmer's production of organic matter. Much has been accomplished in this direction. It is very probable that adequate research by chemists and biologists will result in still further conservation of these valuable fertilizing materials. Apart from sewage, there are other waste products to be considered, such as smelter gases, etc.

Plant and Animal Breeding

One of the most important advances in biological research in recent years is involved in the discovery of the significance of chromosomes, the gene hypothesis, polyploidy, and in general the mechanism of genetics. The amazing results obtained from the development and application of genetics to the corn plant offer a striking example. At present, about 65 percent of the corn acreage in the corn belt of the United States uses hybrids which are distinctly superior in yield, resistance to weather and disease and in quality to the open-pollinated varieties of corn. This great movement is a direct outgrowth of the fundamental genetic researches on the effects of inbreeding and cross-breeding.

Without genetic knowledge, hybrid corn would probably have been long delayed because the first step—selecting parent lines in self-pollinated stocks—appears to be sharply away from rather than toward the goal of better corn. Now the corn breeder is approaching a position in which he can synthesize hybrid strains especially well suited for various industrial purposes—e. g., sirups, dextrose, alcohol, plastics, etc.

Resistance to *Fusarium conglutinans*, the fungus which causes cabbage yellows, is another discovery of gene relationship that makes possible continuance of cabbage production in various old producing regions of the United States in which the soil-borne organism has become thoroughly established. In a similar way, the pea-canning industry has made use of the discovery of a dominant gene conferring immunity to common pea wilt (*Fusarium orthoceras* var. *pisi*). Ten years ago the industry was threatened with failure from the lack of a supply of raw materials as a result of the wide prevalence of this soil-borne fungus. Several seed companies and experiment stations have since supplied a full line of varieties in which this gene is incorporated, so that the problem is no longer important.

Breeding for disease resistance is only a small part of the work of the geneticists. Among the new developments in this field mention should be made of the production of auto and allopolyploidy by the use of heat, colchicine and various well-known chemical substances, including some of the auxins. An illustration may be mentioned; the seed houses now offer for sale newly developed polyploid marigolds.

Many examples may be cited from the animal kingdom; the cross-breeding program of the poultry industry is a good illustration of the application of genetics.

In order to combine the good qualities of two breeds of poultry, the following cross is made: Barred Plymouth Rock males are crossed with New Hampshire females. The cross results in a barred, quick-feathering individual showing rapid growth and reduced mortality. The market value of the first generation individuals is high because of rapid growth and rapid feathering.

Another example of genetic information may be drawn from the use of sex-linked genes for distinguishing the sex of chicks at hatching. One important means is found in the recessive sex-linked gene for long primary and secondary feathers in contrast to the dominant short primaries and secondaries of certain breeds. At least one well-known hatchery has been offering autosexed chicks for sale on the basis of this genetic test. Likewise, a dominant sex-linked gene for barring of feathers has served as a means of distinguishing the sexes at hatching. At hatcheries it is important to know which of the chicks are male and which are female, so that the cockerels may be sold and the pullets be kept for egg production.

The application of the principles of genetics to various problems in plant and animal biology has led to an astonishing increase in productivity and in the improvement of the product.

Training of the Industrial Biologist

The expanding of the general body of knowledge through training in the fundamental disciplines becomes increasingly important. The industrial biologist must have a solid foundation of chemistry and physics to supplement biology so that he may think correctly regarding living things (that are not reagents in a bottle) in terms of their fundamental life processes and reactions. The superstructure will of necessity be varied. It may be anatomy, gross or microscopic; physiology, broad or in its narrower phases of endocrinology; it may be microbiology, represented by bacteriology, virology, parasitology, protozoology. It may be evolution as in genetics, nutrition, broad or narrow, and it may be the interaction of all phases of the environment on one form, ecology. In food research, apart from the background subjects, the biologist should have knowledge of the recent developments in genetics, histology, and plant pathology. The most important thing is the scientific and philosophical foundation on which any desired kind of a structure can be built, and onto which another can be moved to replace the first. While the schools can supply a relatively permanent foundation, the first superstructure will need constant remodeling to meet changing needs and new developments. More emphasis should be placed on the supposedly fixed parts of the endeavor rather than on details and decoration. The universities must maintain great teachers and continue the development of fundamental research.

Biologists specialize in one or more branches of the general field and call themselves according to their major subject; e. g., bacteriologists, cytologists, endocrinologists, parasitologists, and so on. Some of the main divisions and subdivisions follow:

Anatomy.
Bacteriology.
Botany.
Cytology.
Dendrology.
Ecology.
Embryology.
Endrocrinology.
Entomology.
Epidemiology.
Genetics.
Helminthology.
Histology.
Hydrobiology.
Immunology.
Limnology.
Microbiology.
Mycology.
Paleobotany.
Paleontology.
Parasitology.
Pathology.
Pharmacognosy.
Pharmacology.
Physiology.
Plant Pathology.
Protozoology.
Psychology.
Toxicology.
Zoology.

These various subjects emphasize a special sphere of the more general subject of botany or zoology. Often these are disconnected and fail to give the student a well-coordinated outline of the subject as a whole. One obvious feature of all biological study is the multiple interaction of numerous factors that go to make up the general pattern of life. The biologist must always keep in mind that every organism is a dynamic entity formed into a more or less stable pattern. He is working with life and must not forget the complexity of the system and also that no sharp line can be drawn between the organism and its immediate surroundings.

The course work given in chemistry and physics is often organized to train professionals in these fields and not to train persons who wish to learn chemistry, physics, and mathematics as an aid to some other profession. The biologist has great need for physics, chemistry, and mathematics as well as for good foundation in the biological sciences, but he may not have time to pursue the same instruction usually given for the major students in chemistry, physics, and mathematics. A more modest offering in number of divisions with emphasis on the fundamental science, seems desirable.

From what has gone before, it is clear that the research worker in biology should have a broad and fundamental training. Similarly it is essential that the personnel in charge of the scientific control of a biological process, and the officials directing government regulatory activities have fundamental and comprehensive biological training. Too often application of the results of research is unduly delayed or frustrated by the lack of adequately trained personnel to carry the work beyond the laboratory.

The social implications of biological research have not received general recognition. Fortunately, there is growing up a certain awareness among research workers of the impact of discovery upon social organization and welfare. The problems that may develop from research in biology and their social consequences deserve consideration. There is reason to believe that the biologist of the future will consider carefully the social and economic influences that may result from his researches.

Is it possible to train individuals for such a broad field? The answer must come from biological departments in the colleges and universities throughout the country. It is their opportunity and their responsibility to develop the inquisitive mind as well as to point out the application of scientific discoveries to industry.

Trends in Biological Research and New Developments

The history of biology is marked by many changes in the major lines of investigation. Beginning with systematic reports on classification, there have been periods of intensive study of various subjects, depending upon the powerful personality and creative mind of a great leader and the discovery and application of new and important apparatus or methods; the microscope; the Mendelian method of investigating inheritance; the concept of hydrogen-ion concentration, etc. These and other discoveries have exerted a profound influence on the development of biological research. Biology originally was limited to a study of plants or animals as they occur in nature—"natural history." Now biologists are concerned with the experimental approach or with a study of the nature and mode of action of the living organism.

The recent development in food research illustrates this point. The studies have been made along two lines: (1) Investigations relating to raw materials, the production of varieties adapted to special conditions, and (2) investigations of various methods for processing, e. g., quick freezing of fruits, vegetables, and meats; the storage and transportation of food products in an atmosphere rich in carbon dioxide and nitrogen but low in oxygen and at low temperatures.

The study of enzymes, their properties, mode of action and their role in normal and pathological conditions is one of the attractive fields of investigation. The great problem is to get these agents in purified form and to study their properties.

The manufacture of hormones for the treatment of disturbances in metabolism and stimulating the growth of both plants and animals is another important industry that requires the attention of research workers broadly trained in biology and chemistry.

There exists today a growing appreciation of the importance of viruses and of the need for further research. This subject may be divided into three main lines: (1) The general properties of viruses; (2) methods of infection; (3) the occurrence of viruses in diseases. The cultivation of viruses on the chorio-allantoic membrane of the developing chick embryo and by other methods has proved an invaluable tool and already the practical applications are so important that extensive investigations are planned in this field.

The development of sulfanilamide and related compounds has opened the door to a better understanding of the value of certain chemical compounds in the treatment of diseases. Chemotherapeutic agents used in the treatment of streptococcal infections, pneumonia, and meningitis have also produced amazing results. At present the organic chemists and biologists are carrying on extensive investigations in this field.

One of the most significant trends is that of vitamin research. The discovery of better and more sensitive methods for detecting symptoms of a deficiency of the vitamins has been one of the major aims of recent research. An entirely new concept is now developing. The vitamins are but part of an enzyme mechanism involving usually a protein combination. The function and interaction of these systems in the living organism offer a challenge to the investigator.

Fundamentally these developments have been a result of the break with tradition and the liberation of men's minds which occurred during the fourteenth and fifteenth centuries. Freedom of initiative and enterprise have permitted the application of basic discoveries to human welfare. The swing of the pendulum is now in the other direction and in many countries the increasing authority of government may hamper and delay or discourage new developments. Sympathetic cooperation between government and industry and maintenance of a symbiotic relationship between State-controlled and privately controlled research laboratories must be fostered if the fruits of our expanding system of knowledge are to be enjoyed by all. But men of thorough scientific training, wide vision, and sound ethics must staff these organizations for effective results.

There exists extensive opportunity for the biologist who has a broad fundamental knowledge of chemistry and a close acquaintance with physics in addition to a well rounded training in general biology.

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SECTION VI

4. INDUSTRIAL MATHEMATICS

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ABSTRACT

The report consists of three major sections. The first discusses mathematical specialists in industry, calls attention to the essentially consultative character of their work, and makes some observations regarding the education, employment, and supervision of this type of personnel.

The second section deals, not with the work of these specialists, but with the uses to which mathematics is put at the hands of industrial workers in general, the various ways in which it contributes to the economy and effectiveness of research, and the kinds of mathematics that are most used. A number of illustrations are given, together with brief surveys of the utilization of mathematics in four important industries: communications, electrical manufacturing, petroleum, and aircraft.

The third section is devoted to statistics, which touches industrial life at rather different points, and hence could not conveniently be included in the general discussion.

Introduction

Mathematical technique is used in some form in most research and development activities, but the men who use these techniques would not usually be called mathematicians.

Mathematicians also play an important role in industrial research, but their services are of a special character and do not touch the development program at nearly so many points.

Because of this contrast between the ubiquity of mathematics and the fewness of the mathematicians, this report is divided into sharply differentiated parts. Under "Mathematicians in Industry" an attempt is made to explain what sort of service may be expected of industrial mathematicians, and to develop some principles of primary importance in employing and managing them. An attempt is also made to appraise future demand for men of this type, and to discuss the sources from which they can be drawn. Under "Mathematics in Industry" appear brief surveys of the extent and character of the utilization of mathematics in a few special industries, and examples of specific problems in the solution of which mathematical methods have been necessary or advantageous.

In these two sections mathematics is interpreted broadly to include not only the fundamental subjects, algebra, geometry, analysis, etc., but also their manifestations in applied form as mechanics, elasticity, electromagnetic theory, hydrodynamics, etc. Statistics, however, touches industrial activity in a rather different way, and is therefore discussed separately under a third heading, "Statistics in Industry."

One observation which will be made in more detail later is worthy of mention here, because of the present and prospective scarcity of suitably trained industrial mathematicians. Though the United States holds a position of outstanding leadership in pure mathematics, there is no school which provides an adequate mathematical training for the student who wishes to use the subject in the field of industrial applications rather than to cultivate it as an end in itself. Both science generally, and its industrial applications in particular, would be advanced if a group of suitable teachers were brought together in an institution where there was also a strong interest in the basic sciences and in engineering.

Mathematicians in Industry

What is a Mathematician?

If every man who now and then computes the average of a set of instrumental readings or solves a differential equation is a mathematician, there are few research workers who are not. If, on the other hand, only those who are primarily engaged in making additions to mathematical knowledge are mathematicians, there are almost none in industry. Neither definition is sound. The first is absurd; the second not closely related to the essential nature of mathematical thought. This report adopts a definition based upon the character of the man's thinking rather than the ultimate use to which his thinking is put.

Some men would be called mathematicians in any man's language; others physicists or engineers. These *typical* men are differentiated in certain essential respects:

The typical mathematician feels great confidence in a conclusion reached by careful reasoning. He is not convinced to the same degree by experimental evidence. For the typical engineer these statements may be reversed. Confronted by a carefully thought-out theory which predicts a certain result, and a carefully performed experiment which fails to produce it, the typical mathematician asks first, "What is wrong with the experiment?" and the typical engineer, "What is wrong with the argument?" Because of this confidence in thought processes the mathematician turns naturally to paper and pencil in many situations in which the engineer or physicist would resort to the laboratory. For the same reason the mathematician in his "pure" form delights in building logical structures, such as topology or abstract algebra, which have no apparent connection with the world of physical reality and which would not interest the typical engineer; while conversely the engineer or physicist in his "pure" form takes great interest in such useful information as a table of hardness data which may, so far as he is aware, be totally unrelated to any theory, and which the typical mathematician would find quite boring.

A second characteristic of the typical mathematician is his highly critical attitude toward the details of a demonstration. For almost any other class of men an argument may be good enough, even though some minor question remains open. For the mathematician an argument is either perfect in every detail, in form as well as in substance, or else it is wrong. There are no intermediate classes. He calls this "rigorous thinking," and says it is necessary if his conclusions are to be of permanent value. The typical engineer calls it "hair splitting," and says that if he indulged in it he would never get anything done.

The mathematician also tends to idealize any situation with which he is confronted. His gases are "ideal," his conductors "perfect," his surfaces "smooth." He admires this process and calls it "getting down to essentials"; the engineer or physicist is likely to dub it somewhat contemptuously "ignoring the facts."

A fourth and closely related characteristic is the desire for generality. Confronted with the problem of solving the simple equation $x^3-1=0$, he solves $x^n-1=0$ instead. Or asked about the torsional vibration of a galvanometer suspension, he studies a fiber loaded with any number of mirrors at arbitrary points along its length. He calls this "conserving his energy"; he is solving a whole class of problems at once instead of dealing with them piecemeal. The engineer calls it "wasting his time"; of what use is a galvanometer with more than one mirror?

In the vast army of scientific workers who cannot be tagged so easily with the badge of some one profession, those may properly be called "mathematicians" whose work is dominated by these four characteristics of greater confidence in logical than experimental proof, severe criticism of details, idealization, and generalization. The boundaries of the profession are perhaps not made sharper by this definition, but it has the merit of being based upon type of mind, which is an attribute of the man himself, and not upon such superficial and frequently accidental matters as the courses he took in college or the sort of job he holds.

It is, moreover, a more fundamental distinction than can be drawn between, say, physicist, chemist, and astronomer. That is why the mathematician holds toward industry a different relationship than other scientists, a relationship which must be clearly understood by management if his services are to be successfully exploited.

The Place of the Mathematician in Industrial Research

The typical mathematician described above is not the sort of man to carry on an industrial project. He is a dreamer, not much interested in things or the dollars they can be sold for. He is a perfectionist, unwilling to compromise; idealizes to the point of impracticality; is so concerned with the broad horizon that he cannot keep his eye on the ball. These traits are not weaknesses; they are, on the contrary, of the highest importance in the job of finding a system of thought which will harmonize the complex phenomena of the physical world, that is, in reducing nature to a science. The job of industry, however, is not the advancement of natural science, but the development, production, and sale of marketable goods. The physicist, the chemist, and especially the engineer, with their interest in facts, things, and money are obviously better adapted to contribute directly to these ends. To the extent that the mathematician takes on project responsibility, he is forced to compromise; he must specialize instead of generalize; he must deal with concrete detail instead of abstract principles. Some mathematicians cannot do these things at all; some by diligence and self-restraint can do them very well. To the extent, however, that they succeed along these lines they are functioning not as mathematicians but as engineers. As mathematicians their place in industry is not to supply the infinite attention to practical detail by which good products, convenient services, and efficient processes are devised; their function is to give counsel and assistance to those who do supply these things, to appraise their everyday problems in the light of scientific thought, and conversely to translate the abstract language of science into terms more suitable for concrete exploitation.

In other words, the mathematician in industry, to the extent to which he functions as a mathematician, is a consultant, not a project man.

Qualifications Necessary for Success as an Industrial Mathematician

The successful industrial mathematician must not only be competent as a mathematician; he must also have the other qualities which a consultant requires:

First, though his major interests will necessarily be abstract, he must have sufficient interest in practical affairs to provide stimuli for useful work and to reconcile him to the compromises and approximations which are necessary even in the theoretical treatment of practical problems. This usually means that the type of mathematician who could not do a good engineering job if he turned his hand to it will not get on very well in an industrial career.

Second, he must be gregarious and sympathetic. If he shuts himself off from his associates, much of his thinking will have no bearing on their needs and that which does will exert less influence than it might. If he does not translate his thoughts into their language, they will miss the significance of much of his work and he will have but a limited clientele.

Third, he must be cooperative and unselfish. A man cannot be at once consultant and competitor to his associates. Self-seeking attempts to gain credit for his contributions to the industry will inevitably alienate his clientele. There are two reasons for this: In the first place a mathematician's appraisal of mathematical work, even if made from a detached point of view, is heavily weighted on the side of its fundamental scientific significance, whereas its industrial value should be judged on very different grounds and can best be appraised by the engineer. In the second place, the engineer in charge of a project can give credit without embarassment for help received; it is to his credit to have known where help was to be had. The same story told by another, and particularly by the consultant himself, has an entirely different flavor.

Fourth, he must be versatile. Jobs change, and even the same job may give rise to questions which require very different mathematical techniques.

Fifth, he must be a man of outstanding ability. No one wants the advice of mediocrity. Among industrial mathematicians there is no place for the average man.

Employment and Supervision

Perhaps the greatest hazard in hiring mathematicians for industry arises from the fact that the employment officer is not often a judge of mathematical ability. Paradoxically, however, his mistakes are not usually made in judging mathematical aptitude, since general scholastic rating is an unusually trustworthy index of mathematical ability. But because of a feeling of incompetence bred by his lack of mathematical lore, he spreads the mantle of charity over other characteristics with regard to which he should trust his own judgment. If, for example, the applicant gives an incoherent account of the problems on which he has been working, the interviewer excuses it on the ground of his own lack of mathematical training, an excuse which would be quite adequate if the circumstances demanded that he meet the applicant on the applicant's ground. What he overlooks is that the applicant has failed to meet him on his own ground; has failed, in other words, to display the essential ability to translate his thoughts into the language of his hearer. Or perhaps a personality defect is excused on the ground that "after all, he will be working by himself and won't have to meet people," whereas in fact the real value of a consultant comes not in what he does at his desk, but in how much of it gets through to his associates. The applicant who is boastful or pushing or querulous should not be hired on the general theory that "all mathematicians are queer."

High standards in all such matters, and an interest in practical things as well, are as important as technical mathematical ability. These are stiff specifications, and the men to fill them are not to be found in every market place. They are, however, the requirements implicit in the nature of the job and no good can come from failing to recognize them.

After the right man is hired, he is not a difficult person to supervise if his function as a consultant to the rest of the staff is kept clearly in mind. The broad objectives must be to avoid barriers which would tend to deter his associates from seeking his services, and to assure that his work is justly appraised and fairly compensated.

The three barriers most likely to arise between him and his associates are jealousy, red tape, and unavailability.

Jealousy is unavoidable if the man himself is self-seeking; once such a man is hired trouble is inevitable. But the man is not always to blame. A generous and cooperative recruit will be spoiled by an atmosphere too highly charged with progress reports, or by a salary policy which bases revisions upon the dollar value of the last year's work. Actually the "progress" which is significant to management will be far more accurately appraised by his colleagues than by himself, hence his reports have little value except as they give him an opportunity to review and criticise his own activities. If too much emphasis is placed upon them, even this value will be lost and they will be written in the spirit of making a case for himself, which is exactly the spirit most certain to breed jealousy. Similarly, a salary policy based on dollar returns is essentially unjust, for the money value of various bits of theoretical work has almost no correlation with the scientific acumen which they require. This does not mean that a mathematician's pay should, in the long run, be independent of the dollar value of his services. It means only that whether he gets a raise this year, and how big it shall be, should properly be based on the size, character and satisfaction of his clientele, and not upon the commercial importance of the questions they saw fit to bring him last year.

Red tape is easily avoided by avoiding it. No engineer, whatever his rank in the organization, ought ever need permission to consult a mathematician in the company's employ, and the mathematician in turn ought not need a specific work order or expense allowance before giving his advice. In this respect he should be on the same basis as the free lance investigators who are to be found in most large research laboratories, and who are generally known as staff engineers.

Unavailability is a more serious matter. It is well recognized that in industrial research the urgent job always tends to take precedence over the important one. Left to themselves, fundamental studies give way to the detailed development "which ought to go into production next month." Mathematical studies are no more susceptible than other fundamental research to such interruptions, but the effect upon the career of the mathematician may be more far reaching, for as soon as he is assigned an urgent project of special character his availability as a consultant ceases or at best is temporarily impaired. If his value to the industry is greater as a project man than as a consultant this need not be a cause for regret; but to turn a good mathematician into a poor engineer, or an irreplaceable mathematician into a replaceable engineer, is unfortunate for both employer and employee.

The Mathematical Research Department of the Bell Telephone Laboratories

In the Bell Telephone Laboratories, men of this type have been grouped together as a separate organization unit. They have no more specific function than to be helpful to their associates in other parts of the Laboratories. No engineer is obliged to consult them about any phase of his work; no particular jobs come to them by reason of prerogative; conversely, there is no sort of help which an engineer or physicist may not seek from them if he so desires. No routine need be complied with in advance in order to secure their services, and no report is required afterwards, though written reports are frequently prepared when needed for scientific record. The expense of the group is distributed broadly over the activities of the Laboratories, not charged to specific jobs. Every effort is made to maintain a spirit of service among the members of this group, and though responsibility for engineering projects occasionally descends upon them, it is regarded as an undesirable necessity to be avoided whenever possible and liquidated at the earliest opportunity.

The group has functioned successfully for a number of years. Its members are respected by their engineering associates, and like their jobs. Information regarding their activities reaches management almost entirely through spontaneous acknowledgments made by the engineers they assist. These expressions of appreciation are generous, but rather erratic in that they concentrate attention first on one man, then on another, as the genius and training of the individual happen to click with the important job of the moment. This has not affected the morale of the group adversely, probably because a serious effort is made to avoid erratic salary revisions in which the man who is at the moment in the limelight benefits at the expense of others who are doing equally good but less conspicuous work.

From the standpoint of the men, the principal advantages of being associated together instead of distributed through the engineering departments, is the stimulus of contact with men of like interests. From the standpoint of management, the advantages are wider availability, greater flexibility in matching the talents of the man with the requirements of the job, and a more uniform appraisal of ability because of supervision by a man of adequate mathematical background.

So far as is known, mathematicians have not been organized into separate administrative groups in other industries. In most laboratories their numbers have been thought too small to make such an arrangement feasible, and they have been treated as staff engineers distributed throughout the various general departments. It is believed, however, that there are a few industries in which this arrangement could be introduced with profit at this time, and that it has sufficient merit to justify its adoption wherever possible.

The Mathematician in the Small Laboratory

What has been said above relates primarily to conditions in large industries. The qualifications for success in the small industry are not dissimilar, though the relative emphasis to be placed upon them is somewhat different. Matters of personality (gregariousness, unselfishness, etc.) are not quite so important, because they are offset to some extent by the friendly coherence of the small group. On the other hand, a strong interest in things as well as ideas, and the ability to translate from the language of concrete experience to that of abstract thought and conversely, take on even greater importance. As Dr. H. M. Evjen, himself a worker in a small laboratory, says:

> In order to be of optimum value, the mathematician must keep in close touch with realities. In a sufficiently large organization, employing both theoretical and experimental men, the best results, therefore, can be obtained only by the closest cooperation between the two groups. In smaller organizations, employing—for instance—only one scientifically qualified man, it is difficult to say whether this man should be of the theoretical or the experimental type. If he is a theoretical man, no success can be expected unless he is willing to roll up his sleeves and get his feet firmly planted on the ground. In fact, even if he has highly qualified experimental assistants, he should not feel averse to "getting down in the dirt." Secondhand information is always of inferior quality * * *
>
> The mathematician not only is useful as an auxiliary to whom the practical man can turn with special problems. A properly trained mathematician, with a sufficiently broad vision, can be very much more useful as an active participant in the industrial problems. Due to his training in exact thinking he should be better able to see through the maze of intricate details and discover the fundamental problems involved.

Number Employed

The number of mathematicians employed in communications, electrical manufacturing, petroleum, and aircraft, is estimated at about 100. The number employed in other places is no doubt somewhat less, but it is probably not an insignificant part of the whole, since mathematicians are found here and there in some very small industries. For example, the Brush Development Company with a total engineering force of only 17, has found it desirable to supplement this group with a man hired specifically as a consultant in mathematics.

It is perhaps not too wide of the mark to estimate the total number at 150, not including actuaries and statisticians.

This number can be checked in another way. The membership list of the American Mathematical Society lists 202 men with industrial addresses. Of these, 102 are in financial and insurance firms and are presumably statisticians. The remaining 100 names are those of industrial employees with mathematical interests strong enough to belong to an organization devoted exclusively to the promotion of mathematical research. Some of these are not mathematicians by the definition adopted in this report. On the other hand, there are also 158 names for which only street addresses are given, some of whom are known to be industrial mathematicians. Balancing these uncertainties against one another, and remembering that many industrial mathematicians find little profit in belonging to an association devoted primarily to pure mathematics, the estimate given above does not appear unreasonable.

Future Demand

The appraisal of future demand is even more speculative than the estimation of present personnel. Two statements, however, seem warranted: (1) The demand for mathematicians will never be comparable to that for physicists, chemists or engineers. (2) It will certainly increase beyond the number at present employed.

The first statement is justified by the fact that physicists, chemists, and other experimental workers deal directly with the natural laws and natural resources which it is the business of industry to exploit, whereas mathematicians touch these things only in a secondary way.

The second statement would perhaps be granted on the general ground that throughout the whole of industry research is becoming more complex and theoretical, and hence the value of consultants in general, and of mathematical consultants in particular, must increase. It is not necessary, however, to rely solely on such general considerations. Direct evidence exists in certain industries, notably aircraft,[1] where many of the major research problems are generally recognized to be more readily accessible to theoretical than experimental study, and in certain others, such as industrial chemistry,[2] where one may reasonably assume that modern molecular physics will soon begin to play an important part in determining speeds of reaction. There is also the general alertness of executives to the dollar value of a theoretical framework in planning expensive experiments and the gradually changing attitude toward mathematics that stems from it. As Dr. W. R. Burwell, chairman of the Brush Development Company, writes:

> There is a definite trend toward a greater use of mathematics in industry which is somewhat commensurate with the trend toward the acceptance of research and development departments as necessary adjuncts to successful businesses. It is becoming more and more generally recognized that mathematics is not only a necessary tool for all engineers, physicists and chemists who make any pretense of going beyond strictly observational methods and experimental solutions to their problems but that it is also performing an important function as the recording medium for those generalizations which lay the foundation for the advances of scientific knowledge. * * *
>
> Even in an organization as small as ours, the use as a consultant is really important and we are constantly having instances where the mathematician because of his training is serving as an interpreter of mathematical and physical theories, sometimes influencing the direction of experimental work and sometimes eliminating the need for it.

If, therefore, the estimate of 150 mathematicians in industry at present is realistic, it may not be too wide of the mark to forecast several times that number a decade or so hence.

Source of Supply

Based on these estimates, a demand for new personnel of the order of 10 a year may be predicted. This number sounds small; but if we reiterate that mediocrity

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[1] See pp. 285–266.

[2] See pp. 284–285.

has no place in the consulting field, and that these 10 must be *exceptional* men, it does not seem unreasonable to ask where they may be found.

Most mathematicians now in industry were trained as physicists or as electrical or mechanical engineers and gravitated into their present work because of a strong interest in mathematics. Few came from the mathematical departments of universities. As scientists they are university trained, but as mathematicians they are self-educated.

Their training has not been ideal. Industrial mathematics is being carried on by graduates of engineering or physics not so much because of the value of that training as because of the weakness of mathematical education in America. The properly trained industrial mathematician should have, beyond the usual courses of college grade, a good working background of algebra (matrices, tensor theory, etc.), some geometry, particularly the analytic sort, and as much analysis as he can absorb (function theory, theory of differential and integral equations, orthogonal functions, calculus of variations, etc.). These should have been taught with an attitude sympathetic to their applications and reinforced by theoretical courses in sound, heat, light, and electricity, and by heavy emphasis upon mechanics, elasticity, hydrodynamics, thermodynamics, and electromagnetic field theory. He should understand what rigor is, so that he will not unwittingly indulge in unsound argument, but he should also gain experience in such useful but sometimes treacherous practices as the use of divergent series or the modification of terms in differential equations. He should have enough basic physics and chemistry of the experimental sort to give him a realistic outlook on the power as well as the perils of experimental technique. By the time he has acquired this training he will usually also have acquired a Ph. D. degree, but the degree itself is not now, and is not likely to become, the almost indispensable prerequisite to employment that it is in university life.

There is nowhere in America a school where this training can be acquired. No school has attempted to build a faculty of mathematics with such training in mind. Hence industry has had to make such shift as might be with *ersatz* mathematicians culled from departments of physics and engineering. To make matters worse, a student with strong theoretical interests who enrolls in physics these days is almost certain to spend most of his time on modern mathematical physics, which insists almost as little upon fidelity to experience and experiment as does "pure" mathematics, from which it differs more essentially in matters of language and rigor than of general philosophic attitude. At the moment, therefore, engineering schools must be looked upon as the most hopeful sources of industrial mathematicians.

Historically it is easy to explain how this situation came about. Fifty years ago America was so backward in the field of mathematics that there was not even a national association of mathematicians. A quarter of a century later it was just coming of age in mathematics and was properly, if not indeed necessarily, devoting its entire attention to improving the quality of instruction in the "pure" field. The first faint indications that industrial mathematics might some day become a career had indeed begun to appear, but they were not impressive enough to attract the attention of university executives.

Today we lead the world in pure mathematics, and perhaps also in that other field of mathematics which has somehow come to be known as modern physics. We have strong centers of actuarial and statistical training. But in the field of applied mathematics, which is the particular subject of this report, we stand no further forward than at the turn of the century, and far behind most European countries.

A quarter of a century ago it would have been difficult to find suitable teachers. Just now it could be done, primarily because a number of European scholars of the right type have been forced to come here and a few others have developed spontaneously within our own borders. There are perhaps half a dozen of them, but they are so scattered, sometimes in such unpropitious places, as to have little influence on the development of industrial personnel.

It is unfortunate that no university with strong engineering and science departments has seen fit to bring this group together and establish a center of training in industrial mathematics. We have estimated a demand of about 10 *exceptional* graduates per year. If that estimate is even remotely related to the facts, such a department would have a most important job to do.

Mathematics in Industry

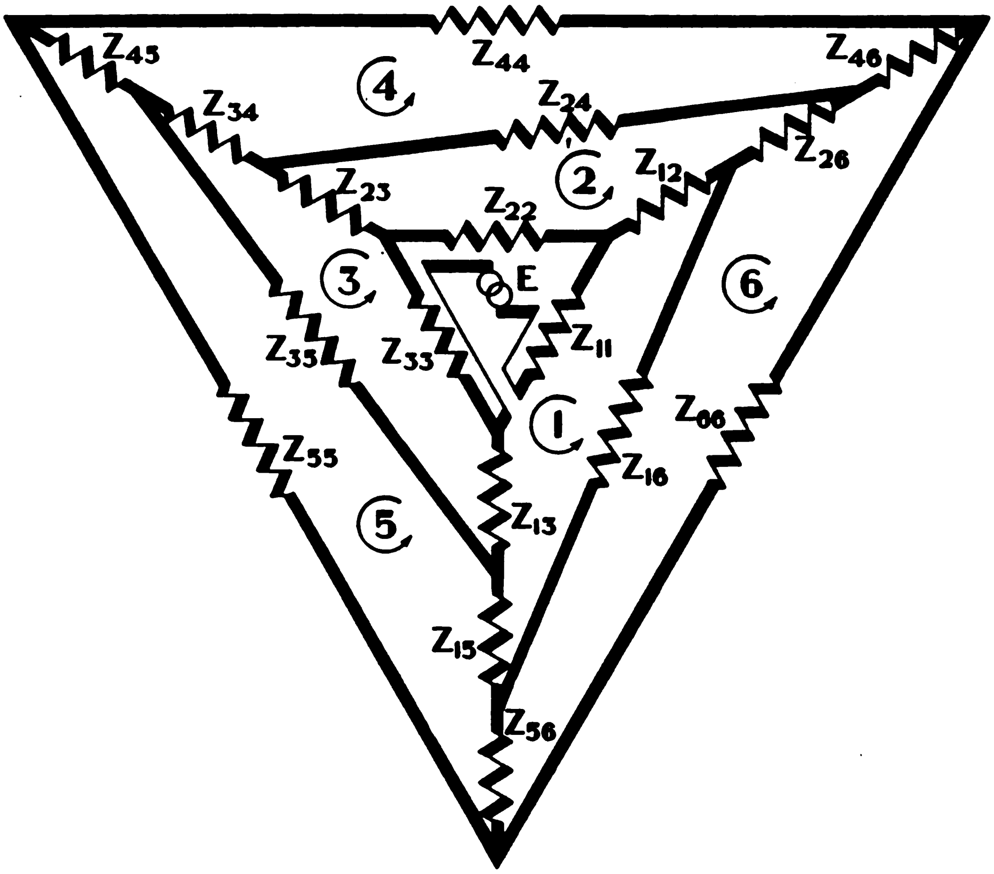
Subjects Used

As Dr. H. M. Evjen, research physicist of the geophysical section of the Shell Oil Company, remarks:

> Higher mathematics, of course, means simply those branches of the science which have not as yet found a wide field of application and hence have not as yet, so to speak, emerged from obscurity. It is, therefore, a temporal and subjective term.

If this is accepted as a definition of higher mathematics—and it is a valid one for the pure science as well as for its applications—it follows automatically that industry relies principally upon the lower branches. What it uses much ceases by the very muchness of its use to be high. The theory of linear differential equations, for example, is a subject by which the average well-trained engineer of 1890 would have been

DETERMINANTS



$$D = \begin{vmatrix} Z_1 & -Z_{12} & -Z_{13} & 0 & -Z_{15} & -Z_{16} \\ -Z_{12} & Z_2 & -Z_{23} & -Z_{24} & 0 & -Z_{26} \\ -Z_{13} & -Z_{23} & Z_3 & -Z_{34} & -Z_{35} & 0 \\ 0 & -Z_{24} & -Z_{34} & Z_4 & -Z_{45} & -Z_{46} \\ -Z_{15} & 0 & -Z_{35} & -Z_{45} & Z_5 & -Z_{56} \\ -Z_{16} & -Z_{26} & 0 & -Z_{46} & -Z_{56} & Z_6 \end{vmatrix} ; Z_j = \sum_{k=1}^{6} Z_{jk}$$

Driving point impedance in mesh j = $Z_{(jj)} = \frac{D}{D_{jj}}$

Transfer impedance between mesh j and mesh k = $Z_{(jk)} = \frac{D}{D_{jk}}$

(D_{jk} = the first minor of the element Z_{jk} in D)

Many properties of the complicated networks studied at Bell Telephone Laboratories are most conveniently expressed by means of determinants. Above are shown a six-mesh network; its "circuit discriminant", D; and some formulae which illustrate how simply the properties of the system can be found from D. Note that, since $Z_{jk} = Z_{kj}$, D is symmetrical.

FIGURE 84

completely baffled. The well-trained engineer of 1940 takes it in his stride and regards it as almost commonplace. The well-trained engineer of 1990 will certainly regard as equally commonplace the theory of analytic functions, matrices, and the characteristic numbers (Eigenwerte) of differential equations, which today are thought of as quite advanced.

With this as a background, there need be no apology associated with the statement that such simple processes as algebra, trigonometry, and the elements of calculus are the most common and the most productive in modern industrial research. They frequently lead to results of the greatest practical importance. The single sideband system of carrier transmission, for example, was a mathematical invention. It virtually doubled the number of long-distance calls that could be handled simultaneously over a given line. Yet the only mathematics involved in its development was a single trigonometric equation, the formula for the sine of the sum of two angles.

Next in order of usefulness come such subjects as linear differential equations (e. g., in studying the reaction of mechanical and electrical systems to applied forces, the strains in elastic bodies, heat flow, stability of electric circuits and of coupled mechanical systems, etc.); the theory of functions of a complex variable (particularly in dealing with potential theory and wave transmission, propagation of radio waves and of currents in wires, gravitational and electric fields as used in prospecting for oil, design of filters and equalizers for communication systems, etc.); Fourier, Bessel, and other orthogonal series (in problems of heat flow, flow of currents in transmission lines, deformation and vibration of gases, liquids and elastic solids, etc.); the theory of determinants (particularly in solving complicated linear differential equations, especially in the study of coupled dynamical systems); and the like.

Less frequently we meet such subjects as integral equations, which has been made the basis of one version of the Heaviside operational calculus and which has also been used in studying the seismic and electric methods of prospecting for oil; matrix algebra, which has been applied to the study of rotating electric machinery, to the vibration of aircraft wings, and in the equivalence problem in electric circuit theory; the calculus of variations, in improving the efficiency of relays; and even such abstract subjects as Boolean algebra, in designing relay circuits; the theory of numbers, in the design of reduction gears and in developing a systematic method for splicing telephone cables; and analysis situs, in the classification of electric networks.

Least frequently of all, but by no means never, the industrial mathematician is forced to invent techniques which the pure mathematician has overlooked. The method of symmetric coordinates for the study of polyphase power systems; the Heaviside [3] calculus for the study of transients in linear dynamical systems; the method of matrix iteration in aerodynamic theory; [4] much of the technique used in the design of electric filters and equalizers—these may stand as illustrative examples.

The student of modern mathematics will be impressed at once by two aspects of this review: first, by the heavy emphasis on algebra and analysis and the almost complete absence of geometry beyond the elementary grade; second, the complete absence of the specific techniques which play such a large role in modern physics and astrophysics. It is not easy to say just why advanced geometry plays no larger part in industrial research; however, the fact remains that it does not.[5] As regards modern physics, one may perhaps extrapolate from past history and infer that what is now being found useful in interatomic physics will soon be needed in industrial chemistry. In making this extrapolation, however, it is well to bear in mind that the physics in question is for the most part a mental discipline, its connection with the world of reality still ill-defined and incompletely understood. Therefore it may not prove to be as quickly assimilable into technology as have other disciplines whose symbols could be more immediately identified with experience.[6]

Finally, we must remark upon two facts: (1) that approximate solutions of problems, and hence methods of iteration (successive approximation), play a much more conspicuous role in applied mathematics than in the pure science; (2) that the highly convenient assumption that linear approximations to natural laws (such as Hooke's law and Ohm's law) are sufficiently exact for practical purposes is less often true than formerly was the case, so that nonlinear differential equations are of great importance to the modern engineer.

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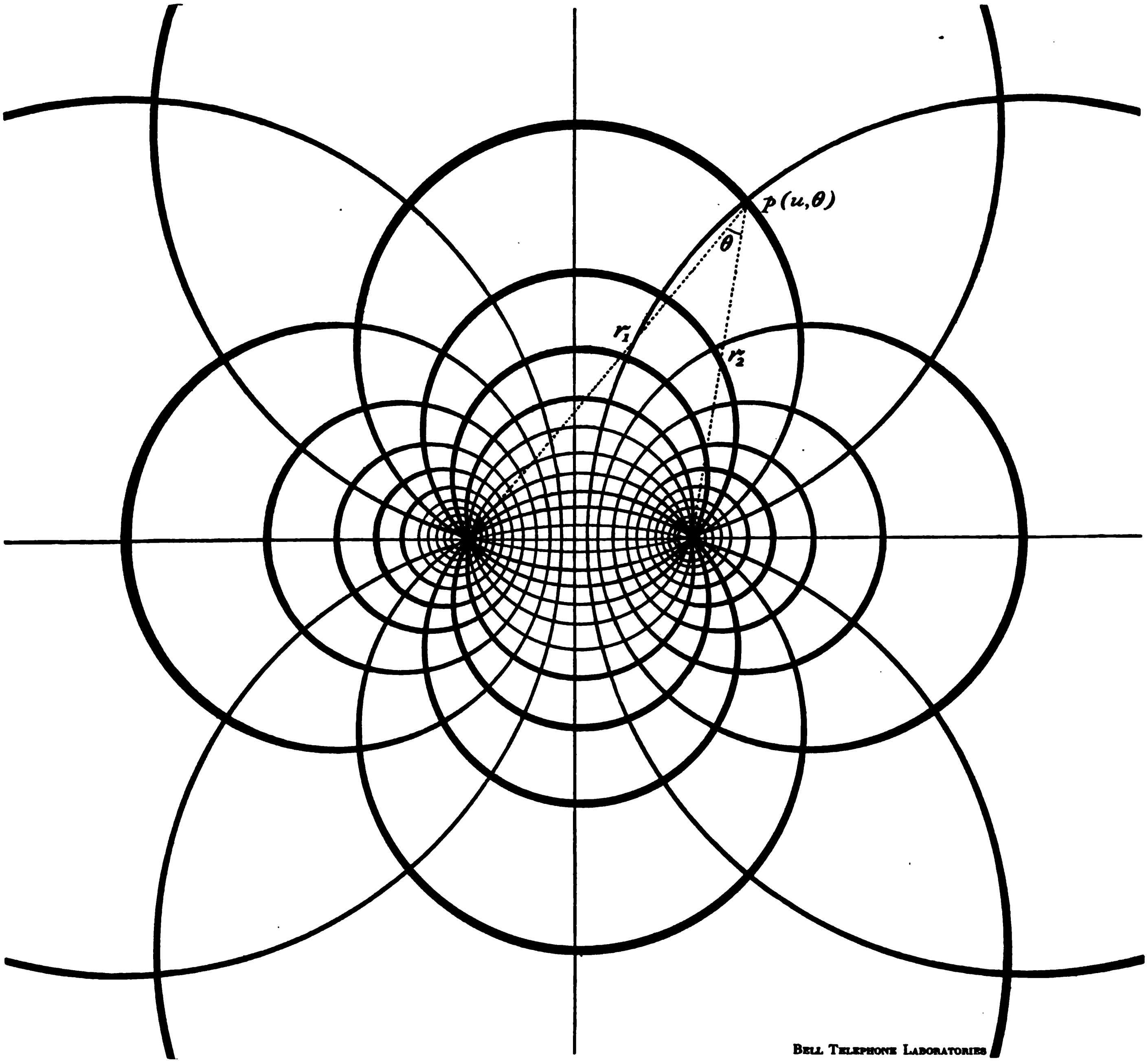
[3] Heaviside was not himself an industrial employee, but the reformulation of his work in terms of integral equations and its interpretation in terms of Fourier transforms were both carried out in America by industrial mathematicians.

[4] This method was developed in the National Physical Laboratory of England, in the course of studies which in America would probably have been undertaken by a Government or industrial laboratory.

[5] Mr. Hall C. Hibbard, of the Lockheed Aircraft Corporation, comments on this remark as follows: "It is possible that the usefulness of this principle of mathematics has been overlooked to a large extent in certain fields where it might be applied to advantage. In particular, that phase of engineering known as "lofting," which deals with the development of smooth curved surfaces, might offer an interesting field for certain types of advanced geometry. Practically all of this work is now done by "cut and try" methods, and the application of mathematics would no doubt save a great deal of time. The same thing is true in the field of stress analysis, where a great deal of time is absorbed in determining the location and direction of certain structural members. It is even possible that the application of vector analysis technique would greatly simplify certain forms of structural analysis, particularly space frameworks. The lack of application of geometry in these fields is probably due to the wide gap that exists between the mathematician and the 'practical' designer and draftsman. Advanced geometry might also turn out to be a very useful tool in connection with problems that we are now encountering in the forming of flat sheet into surfaces with double curvature, an operation that is extensively employed in aircraft manufacture."

[6] In this connection, see the quotation from Dr. E. C. Williams on pp. 284-285.

Bicircular Coordinates



Bell Telephone Laboratories

Figure 85

$$(x+\coth u)^2+y^2=\operatorname{csch}^2 u;\ x^2+(y-\cot\theta)^2=\csc^2\theta$$

$$u=\log(r_2/r_1)$$

Using the bicircular system of coordinates facilitates finding the distribution of electric charge on two parallel conductors, and thence their capacity. Rotating the bicircular system about the vertical axis generates a toriodal coordinate system which facilitates determining the capacity of a torus.

Types of Service Performed by Mathematics

Leaving aside the important but rather trite observation that mathematics is a language which simplifies the process of thinking and makes it more reliable, and that this is its principal service to industry, we may distinguish certain less inclusive, but perhaps for that reason more illuminating, categories of usefulness.

First: It provides a basis for interpreting data in terms of a preconceived theory, thus making it possible to draw deductions from them regarding things which could not be observed conveniently, if at all.

(*a*) An illustration is the standard method for locating faults on telephone lines. Mathematical theory shows that a fault will affect the impedance of the line in a way which varies with frequency and that the distance from the place of measurement to the fault can be deduced at once from the frequencies at which the impedance is most conspicuously affected. This is obviously much more convenient than hunting the fault directly.

(*b*) A second illustration is the mapping of geological strata by means of measurements made upon the surface of the earth. One method extensively employed uses a large number of seismographs, each of which records the miniature earthquake shock produced at its location by a charge of dynamite set off at a known place. A theory of reflection and refraction similar to that used in geometrical optics shows that certain observable characteristics of these records are related to the depth and tilt of the underground layers, and hence enables the situation of these layers to be plotted. By this means the location of the highest point of an oil-bearing stratum can be found and the most favorable position for drilling determined.

Underground geology is also studied by means of gravity, electrical or magnetic measurements upon the surface. In this case the basic theory is that of the Newtonian potential field, and the interpretation of the data leads into the subject of inverse boundary value problems, which is still insufficiently understood. Enough progress has been made in several geophysical laboratories, however, so that the gravity method is now being widely used, and the electrical methods appear promising for some applications.

Second: When data are incompatible with the preconceived theory, a mathematical study frequently aids in perfecting the theory itself. The classical illustration in pure science is the discovery of the planet Neptune. The motion of the planet Uranus was found to be inconsistent with the predictions of the Newtonian theory of gravitation, if the solar system consisted only of the seven planets then known. Mathematical investigation indicated, however, that if an eighth planet of a certain size was assumed to be moving in a certain orbit, these discrepancies disappeared. Upon turning a telescope to the spot predicted, the new planet was found.

An illustration comes from the aircraft industry. I quote it from a report sent me by Mr. C. T. Reid, Director of Education of the Douglas Aircraft Company:

(*c*) The behavior of airplanes with "power on" did not check closely enough with stability predictions which had been made without consideration of the effects of the application of power; therefore, a purely mathematical analysis of the longitudinal motion of an airplane was carried out, involving the solution of three simultaneous linear first-degree differential equations. The results led to the development of equations for dynamic longitudinal stability with "power on" which enable the aerodynamicist more accurately to predict the stability characteristics of a given design. "Power-on" dynamic longitudinal stability is an important design criterion in aircraft construction.

(*d*) Another illustration arises in communication engineering. Theoretical studies had established the fact that vacuum tubes would spontaneously generate noise because of the discrete character of the electrons of which the space current is composed. The theory predicted how loud this noise would be in any particular type of vacuum tube, a most significant result since it established a limit to the weakness of signals which could be amplified by this type of tube. The predictions of the theory were supported by experimental data so long as the tubes were operating without appreciable space charge. But it was found that when space charge was present the noise level fell far below the predicted minimum. In this case the missing factor in the theory was immediately obvious, but an understanding of the mechanism by which the reduction was affected and its incorporation into the theory in a workable form required an extensive and difficult mathematical attack.

Third: It is frequently necessary in practice to extrapolate test data from one set of dimensions to a widely different set, and in such cases some sort of mathematical background is almost essential.

An example of this kind of service, concerned with the theory of arcs in various gases, is furnished me by Mr. P. L. Alger, staff assistant to the vice president in charge of engineering, of the General Electric Company:

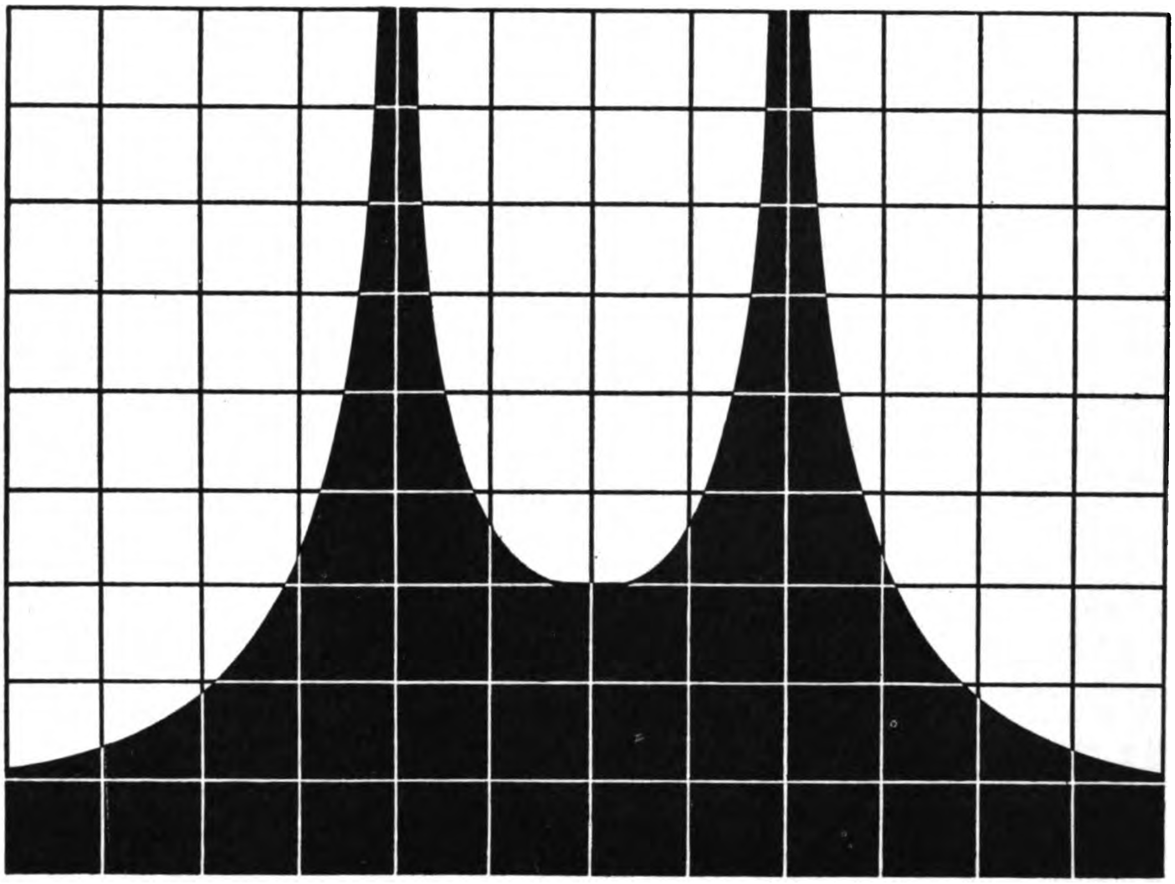
(*e*) An example of this kind of problem is that of the theory of arcs in various gases. It has been experimentally known that the duration, stability and voltage characteristics of electric arcs in different gases and under different pressures vary very widely. The behavior of such arcs is of great importance, both in welding and in the design of circuit breakers and other protective devices. Recently a mathematical theory has been developed which relates the arc phenomena to the heat transfer characteristics of different gases. This theory has given excellent correlation between the known experimental results and has enabled very useful predictions of performance under new conditions to be made. The theory has been applied in the design of high voltage air circuit breakers, which are of important commercial value, and it is also greatly curtailing the time and expense necessary to develop many other devices in which arc phenomena are of importance.

A second example, furnished me by Mr. Reid, has to do with the interpretation of wind-tunnel data in aerodynamics:

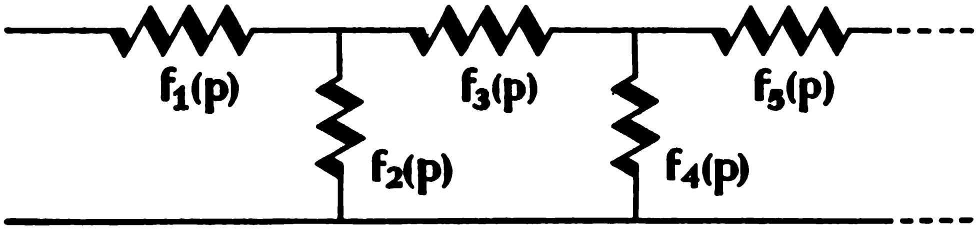
(*f*) Here it is obviously impracticable to perform full-scale tests of such parts as wings or fuselage, much less of entire aircraft, and the extrapolation from the results of wind tunnel measurements to the full-scale characteristics of airplanes must be based on theoretical considerations.

Fourth: Mathematics frequently aids in promoting economy either by reducing the amount of experimentation required or by replacing it entirely. Instances of this kind are met everywhere in industry, not only in research activities but in perfecting the

CONTINUED FRACTIONS



$$Z = f_1(p) + \cfrac{1}{\cfrac{1}{f_2(p)} + \cfrac{1}{f_3(p) + \cfrac{1}{\cfrac{1}{f_4(p)} + \cdots\cdots}}}$$



A mathematical method of systematically designing a circuit of predetermined impedance has been developed in Bell Telephone Laboratories. The given impedance, as a function of frequency, is expanded in a Stieltjes continued fraction, whose terms give the electrical constants of the desired network.

FIGURE 86

design of apparatus and in its subsequent manufacture as well.

Mr. Alger describes in general terms one situation frequently met in research activities as follows:

> The first type of problem is one in which there are so many different independent dimensions of a proposed shape to be chosen, or in general so many independent variables, that it is hopeless to find the optimum proportions by experiment. The truth of this can readily be seen when it is realized that the number of test observations to be made increases exponentially with the number of variables. If 10 points are required to establish a performance curve for one variable, 1,000 observations will be required if there are 3 independent variables, and a million if there are 6 variables.

As an illustration he cites the following problem:

> (*g*) An example of this kind of problem is that of designing a *T* dovetail to hold the salient poles in place on a high speed synchronous generator. A large machine of this type may have 10 or more laminated poles carrying heavy copper field coils, each assembled pole weighing several tons and traveling at a surface peripheral speed of 3 miles a minute. The centrifugal force on each pound of the pole then amounts to approximately 500 pounds. The problem of designing dovetails to hold these poles in place, even at over speed, is, therefore, one of great importance and technical difficulty. For each such dovetail, there are 7 different dimensions which may be independently chosen. While empirical methods have enabled satisfactory results to be obtained in some cases, application of mathematics has recently enabled marked improvements in dovetail designs to be made. Generally speaking, these improvements have permitted an overall strength increase of 20 percent to be obtained under steady stresses and much higher gains to be made under fatigue stress conditions; while at the same time the certainty of obtaining the desired results on new designs has been very greatly enhanced.

A second example was brought to my attention by Mr. L. W. Wallace, Director of the Engineering and Research Division of the Crane Company:

> (*h*) A pipe fitting weighing several hundred pounds and intended for high pressure service had a neck of elliptical cross-section. As originally designed, the thickness of the casting was intentionally not uniform, the variations having been introduced empirically to strengthen it where strength was supposed to be most needed. A redesign carried out on the basis of the theory of elasticity showed the distribution of metal to be inefficient and resulted in a new casting in which the weight was reduced by half, while at the same time the bursting strength was doubled. The method used in arriving at this result is an interesting illustration of sensible mathematical idealization. The casting was regarded as an elliptical cylinder under hydrostatic pressure. As the stresses for this idealized structure were already known, the design problem reduced at once to the simple matter of establishing thicknesses sufficient to withstand these stresses.

Another example from the field of geophysical prospecting is furnished by Mr. Eugene McDermott, President of Geophysical Service Inc.:

> (*i*) A specific case of mathematical research in instrument design was recently encountered. The instrument in question was intended for the measurement of gravity. After the machine had been completely built it was found to be unexplainably inaccurate. After weeks of trial and error it was turned over to a mathematician to try to find the trouble. He soon showed by simple trigonometry that the axis of the instrument would have to be located on its pivot with an accuracy which is not attainable. He also pointed out a means of avoiding this feature by a relatively simple change in design, and this appears to have remedied the trouble.

Another illustration from the petroleum industry, but this time concerned with the production of oil rather than prospecting for it, comes from Dr. E. C. Williams, Vice President in charge of research of the Shell Development Company:

> (*j*) The petroleum industry has one important problem not found in other fields; it has to do with oil production from the ground. A mathematical problem arising from this subject is the following: The oil-gas mixture underground flows under pressure through porous media; with a certain spacing of wells, determine the most economical way to recover this mixture. This is sometimes equivalent to asking: "In what way can the largest fraction of the oil be obtained over a certain period of time?" Simplified problems of this kind have been solved by potential theory methods, since classical hydrodynamics becomes too involved, and in the general problems where the flow constants vary with liquid-gas composition, etc., partial differential equations are found which can be solved by approximate methods. On the basis of the solution of this mathematical problem, aided by extensive laboratory determinations of the required constants, one is able to find the best of several ways of producing from a given oil field.

As a final example under the heading of economy, we may mention the flight testing requirements imposed upon the aircraft industry by the Civil Aeronautics Authority. Of these, Mr. E. T. Allen, Director of Flight and Research of the Boeing Aircraft Company, says:

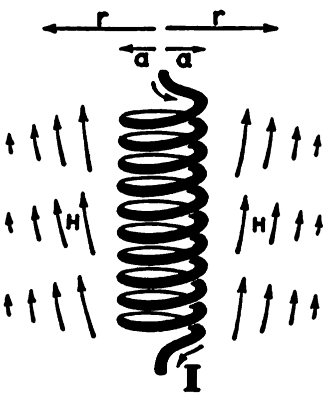
> (*k*) It was formerly required that each type of transport plane must be tested at all the altitudes at which it was intended to be flown, and at all flying fields where it was expected to be used. The cost of such testing was extremely high. A mathematical study of steady flight performance has, however, identified the basic parameters and established their relations to one another. This has made possible a scientific interpretation of flight test data taken at any suitable location convenient to the aircraft factory, and a reliable conclusion therefrom as to the performance to be expected under other conditions. This has greatly reduced both the cost and the time necessary to establish performance figures.

Fifth: Sometimes experiments are virtually impossible, and mathematics must fill the breach. An example comes to me from Mr. Hall C. Hibbard, Vice President and Chief Engineer of the Lockheed Aircraft Corporation:

> (*l*) An unfortunate phenomenon that must be dealt with in aircraft design is a type of violent vibration which may be set up in the wings if the plane is flown too fast. It is known as flutter, and is highly dangerous, since the vibrations may be of such intense character as to cause loss of control or even structural failure. The technical problem is therefore to be sure that the critical speed at which flutter would occur is higher than at any at which the craft would ever be flown. It is a phenomenon

Elliptic Integrals

$$H=\frac{4I}{r}\left[\frac{1}{1-k^2}\int_0^{\pi/2}\sqrt{1-k^2\sin^2\lambda}\,d\lambda-\int_0^{\pi/2}\frac{d\lambda}{\sqrt{1-k^2\sin^2\lambda}}\right]$$



Some simple engineering problems require advanced mathematics in their solution. This is true, for example, in the computation of the magnetic field outside the spiral grid of a vacuum tube, a problem of interest to Bell Telephone Laboratories. If the grid is closely coiled, the current can be treated as a continuous cylindrical sheet, of radius a. Then the component of the magnetic field parallel to the axis of the grid at a distance r from the axis is given by the above function of two Elliptic Integrals whose "modulus" is $k=a/r$.

Figure 87

with respect to which wind tunnel experimentation is difficult and flight testing very dangerous. It has been the subject of a number of mathematical investigations, the results of which have reached a sufficiently advanced stage that they are now being used to predict the critical speeds and flutter frequencies of aircraft while still in the design stage. Even more important, the mathematical investigation of this problem points the way to modifications of design which will insure that flutter cannot occur in the usable speed range.

Telephony provides a second example:

(*m*) The equipment in an automatic telephone exchange must be capable of connecting any calling subscriber with any called subscriber. It consists of several stages of switches, each of which can be caused to make connection with a number of trunks which lead in turn to switches in the next succeeding stage. Enough switches must be provided so that only a very small proportion of subscribers' calls will fail to be served immediately. Since the demands made by the subscribers fluctuate from moment to moment, the number of switches required depends in part upon the height to which the crests occasionally rise in this fluctuating load. It is also influenced, however, by the way the trunks are arranged, by the order in which the switches choose them, and by many other factors. Experimental appraisal of the effect of these various factors is impossible, both because it would be very costly, and because it would be exceedingly slow. Mathematically, however, they have been studied by the theory of *a priori* probability,[7] which is used not only in determining how much apparatus to install in a working exchange, but also in comparing the relative merits of alternative arrangements while in the development stage.

Sixth: Mathematics is frequently useful in devising so-called crucial experiments to distinguish once for all between rival theories. A famous example in the field of physics was the study of the refraction of starlight near the sun's disk, which afforded a means of deciding between Newtonian and relativistic mechanics. In this case, mathematical investigation showed that the result to be expected was different according to the two theories, and astronomical observations confirmed the prediction of relativistic mechanics. In the industrial field, an example of this kind comes to me from Dr. Joseph A. Sharpe, Chief Physicist in the Geophysical Laboratory of the Stanolind Oil and Gas Company:

(*n*) As an example of the second sort of use of analysis there is the case of our study of "ground-roll," the large amplitude, low frequency surficial wave which caused so much grief in the early days of seismic reflection prospecting when filters were not used as extensively as at present. We hope to use our study of this wave motion as an aid to a better understanding of the properties of the surficial layers of soil and their effects on the reflected waves in which we are primarily interested.

Two views on the ground-roll are current, although neither is based on very much observation, and this of an uncontrolled sort. One view states that the ground-roll is an elastic wave. Analysis predicts that this wave will have a certain velocity in relation to the velocities of other waves, that it will have a certain direction of particle motion and relation of maximum horizontal to maximum vertical component of displacement, that it will attenuate with distance according to a certain law, that it will attenuate with depth in a certain way, and that its velocity will follow a certain dispersion law. The second view maintains that the "ground-roll" is a wave in a viscous fluid, and analysis predicts a behavior which is similar in certain cases, and different in others, to that of the elastic wave. Having the predictions of the analysis at hand, we are enabled to devise a group of observations, and the special equipment for their prosecution, which will provide crucial tests of the two hypotheses.

Seventh: Mathematics also frequently performs a negative service, but one which is sometimes of very great importance, in forestalling the search for the impossible; for many desirable objectives in industry are as unattainable as perpetual motion machines, and frequently the only way to recognize the fact is by means of mathematical argument.

(*o*) A certain type of electric wave filter which is usually referred to as an "ideal" filter would be very useful if it could be produced. However, it has been shown mathematically that such a structure would respond to a signal before the signal reached it; in other words, that it would have the gift of prophecy. Since this is absurd, it follows that no such filter can be built, and consequently no one tries to build it.

Still another example from the field of communication deals with the design of feedback amplifiers.

(*p*) In practice, any amplifier is intended to handle signals in a given frequency band. For various reasons, it is preferable not to have it amplify disturbances outside this band, and hence its gain characteristic is made to drop off as rapidly as possible outside the limits of the useful band. It has been shown theoretically, however, that the gain cannot decrease at more than a certain rate, which can easily be computed, without causing the amplifier to become unstable. As a matter of fact, the allowable rate at which the gain may fall is often surprisingly low, and a great deal of design effort would be wasted in the attempt to obtain an impossible degree of discrimination if the theoretical limitations were unknown.

Eighth: Finally, mathematics frequently plays an important part in reducing complicated theoretical results and complicated methods of calculation to readily available working form. So many and so varied are the services falling in this category that it is difficult to illustrate them by means of examples. We arbitrarily restrict ourselves to two, chosen primarily for the sake of variety. The first comes from Mr. Hibbard:

(*q*) In aircraft design the metal skin, though thin, contributes a larger part of the structural strength. Nevertheless, such thin metallic plates will buckle or wrinkle after a certain critical load is exceeded. Beyond this point the usual structural theories cannot be applied directly, and it is therefore necessary to introduce new methods of attack to predict the ultimate strength of the structure. These stiffened plates are difficult to deal with theoretically, but by interpreting the effect of the stiffeners as equivalent to an increase in plate thickness or a decrease in plate width, the calculations can be brought within useful bounds.

The reduction of electric transducers to equivalent T or Π configurations, the interpretation of the elastic reaction of air upon a microphone as equivalent to an increase in the mass of its diaphragm, the postulation of

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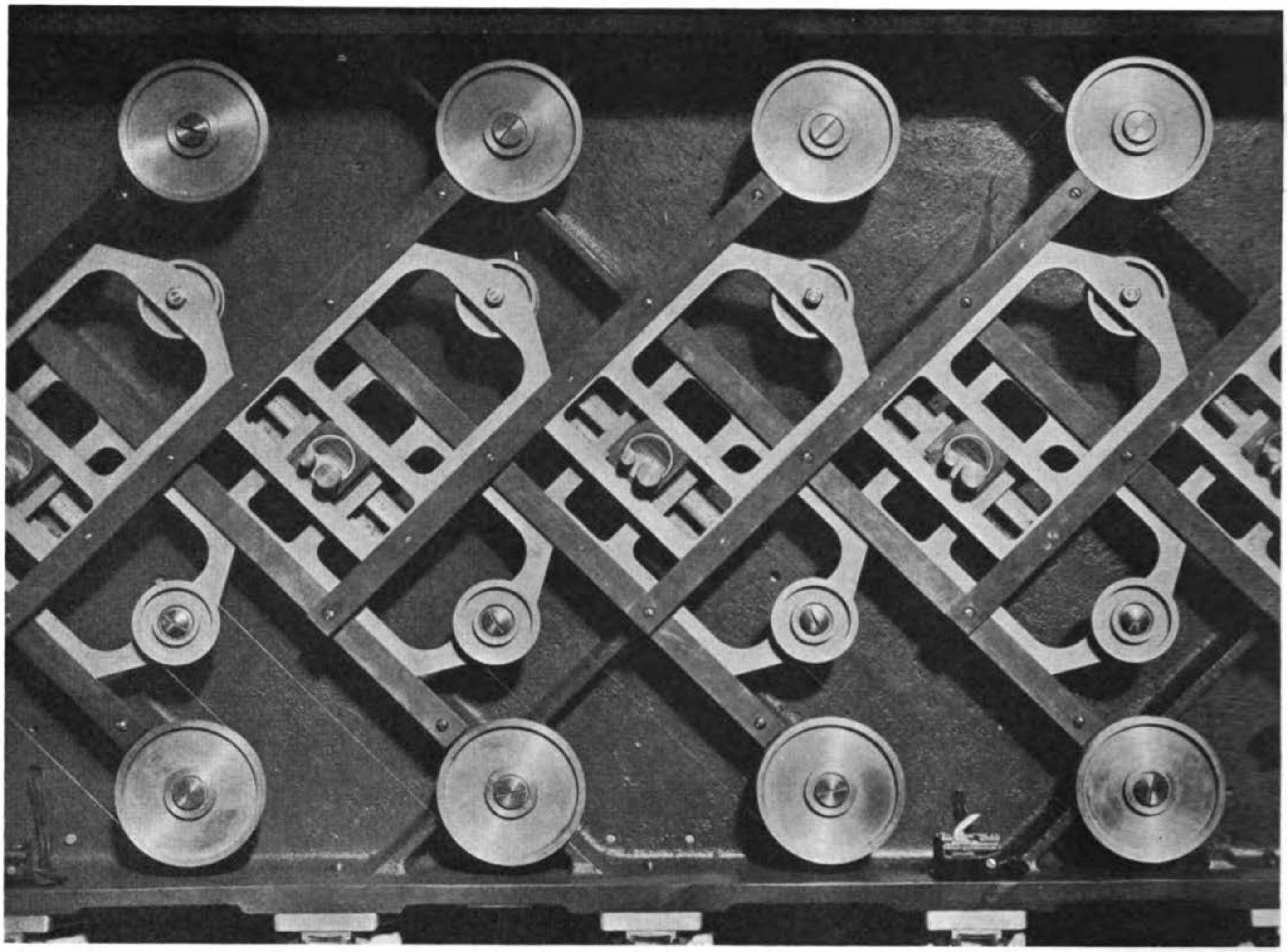
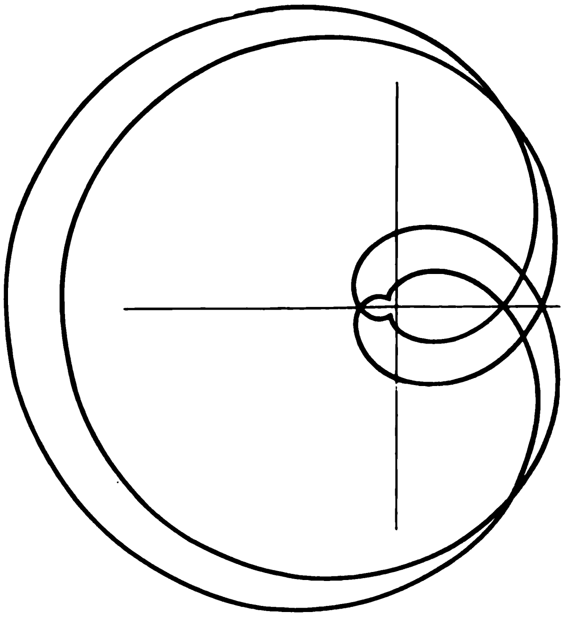
[7] *Not* statistics, which is *a posteriori* probability. This is one of the few cases in industry where the *a priori* theory finds application.



THE ISOGRAPH

The Isograph was developed in Bell Telephone Laboratories to find mechanically the complex roots of polynomials of high degree. Let the polynomial to be factored be $p(z)=\sum_{0}^{n}a_jz^j$ or $\sum_{0}^{n}a_jr^j\cos j\Theta+i\sum_{1}^{n}a_jr^j\sin j\Theta$ if $z=r(\cos\Theta+i\sin\Theta)$. The isograph maps the complex values of $p(z)$ as the variable describes the circle $|z|=r$. This graph loops the origin once for each root smaller in absolute value than r. The number of roots between trial values of r is determined by counting loops, and by interpolation a value of r is found for which the graph passes through the origin. This value of r and the corresponding value of Θ define the real and imaginary parts of a root.



Courtesy Bell Telephone Laboratories

FIGURE 88

an "image current" as a substitute for the currents induced in a conducting ground by a transmission line above it, and a host of other common procedures could be cited as similar instances of simplification based upon more less valid mathematical reasoning.

The second example is furnished by Dr. E. U. Condon, Associate Director of the Research Laboratories of the Westinghouse Electric and Manufacturing Company:

> (*r*) In the manufacture of rotating machinery it is of extreme importance to have the rotating parts dynamically balanced, in order to reduce to a minimum the vibration reaction on the bearings which unbalance produces. Theory shows the phases and amplitudes of the bearing vibrations produced by excess masses located at various places on the rotor; conversely, by solving backward from observed vibration data, one can compute what correction is needed to eliminate the unbalance. Recently a most valuable machine has been developed which not only measures the unbalance, but also automatically shows what correction should be made, thus eliminating the necessity for these calculations.
>
> The rotor to be balanced is whirled in bearings on which are mounted microphones that generate alternating voltages corresponding to the vibrations of the bearings. These voltages are fed into an analyzing network, which automatically indicates the correction needed in order to achieve dynamic balance. In some cases the output of the balancing machine has been arranged to set up a drilling machine so it will automatically remove the right amount of metal at the right place. These machines are finding application in the manufacture of small motors, of automobile crankshafts, and in the heavy rotors of power machines.

In the same class would come the isograph, by means of which the complex roots of polynomials can be located; the tensor gage which registers the principal components of strain in a stressed membrane without advance knowledge of the principal axes; and slide rules for a great variety of special purposes such as computations with complex numbers, the calculation of aircraft performance, aircraft weight and balance, and the like. Perhaps we ought also include in the same category the use of soap-bubble films for the study of elastic stresses in beams, the use of current flow in tanks of electrolyte for the study of potential fields, and the use of steel balls rolling on rubber membranes stretched over irregular supports as a means of studying the trajectories of electrons in complicated electric fields. These are all mechanical methods for saving mathematical labor, but they are more than that, for they all rest upon a foundation of mathematical theory. They are, in fact, examples of the use of mathematics to avoid the use of mathematics.

Mathematics in Some Particular Industries

Communications.—The communication field is the one in which mathematical methods of research have been most freely used. This is due partly to the fact that the transmission of electric waves along wires and through the ether follows laws which are particularly amenable to mathematical study; partly also to the fact that so much of the research has been centralized in a single laboratory, thus bringing together a large number of engineers into a single compact group and justifying the employment of consultative specialists. Most important of all, however, is the fact that there are two devices—vacuum tubes and electrical networks—without which modern long-distance telephony would be impossible; and one of these, the electrical network, is and has been since its earliest days almost entirely a product of mathematical research. Mathematics has thus been as essential to the development of Nation-wide telephony as copper wire or carbon microphones.

Number of Mathematicians: The Mathematical research Department of the Bell Telephone Laboratories contains 14 mathematicians. Perhaps an equal number of men scattered through various engineering departments should also be classified as mathematicians according to the definition adopted for this report. Say a total or 25 or 30 for the Bell Laboratories, a few more for the Bell System as a whole, and perhaps 40 or 50 for the entire communication field including the companies interested in radio and television. A few of these men carry on a considerable amount of experimentation, but their significant work is theoretical.

In addition, there is a much larger number of men who use mathematical methods extensively in their daily work but whose mental type is not that which we have described as mathematical and who are therefore not included in the numbers quoted above. This is true in particular of the engineers who have the responsibility for designing networks.

Uses of mathematics: Mathematical activity is most intense: (1) in designing wave filters and equalizers; (2) in studing transmission by wire and ether, the concomitant problems of antenna radiation and reception, inductive interference between lines, etc.; (3) in studying various problems related to the standard of service in telephone exchanges, such as the amount of equipment required, the probability of delays and double connections, the hunting time of switches, etc.; (4) in providing a rational basis for the design of instruments, such as transmitters and receivers, vacuum tubes, television scanning devices, etc.; (5) in developing efficient statistical methods for the planning and interpretation of experiments and for controlling the quality of manufactured apparatus.

Future prospects: During the last 20 years the number of men employed in communication research has increased with great rapidity, but this rapid expansion appears to be about over. A large increase in the mathematical personnel of the industry therefore appears unlikely. It seems inevitable that the problems will increase in complexity, and that theoretical methods will become increasingly important, but it is believed that this trend will be matched by progressively better trained engineering personnel, rather than by an increased number of mathematicians. Indeed, unless the qualifications of the mathematicians rise progressively with those of the engineers, it may turn out that less rather than more will be employed.

Electrical manufacturing.—Substantially all the research in the power fields is carried on by a few electrical manufacturers. The power companies usually accept and exploit such equipment as the manufacturers supply, and contribute to improved design principally through their criticisms of past performance. Many of their engineers, however, are individually active in the invention and development of improved equipment.

Number of mathematicians: The number of mathematicians in the industry is smaller than in communications, and is not easy to estimate because their work is less segregated from other activities. The total number who would here be rated as mathematicians is probably about 20.

As in communications, some are engaged partly in experimental work. There are some, however, whose relationship as consultants is clearly recognized, and there is evidence that management is becoming increasingly conscious of the nature and value of their services.

Uses of mathematics: Mathematical activity is most intense: (1) in studying structural and dynamic problems, such as the strain, creep, and fatigue in machine parts, vibration and instability in turbines and other rotating machinery, etc., (2) in appraising the evil effects of suddenly applied loads, lightning or faults upon power lines, and their associated sources of power, and devising methods to minimize these effects, (3) in studying system performance, particularly the most effective or economical location of proposed new equipment, and the evaluation of performances of alternative transmission or distribution systems, (4) in refining the design of generators, motors, transformers and the like, so as to improve their electrical efficiency and reliability, and in similar improvement of the thermal efficiency of turbines, (5) in the design of miscellaneous instruments and apparatus.

Statistical methods are being introduced into manufacturing and research, but are not yet utilized to the same extent as in telephony.

Future prospects: The amount of money spent on development in these industries is gradually increasing, and as in other fields the problems are becoming more complex. Hence a slow increase in the number of mathematicians seems probable, with rising standards in the qualifications required, not only as to mathematical training, but as to temperament and personality as well.

The petroleum industry.—The petroleum industry consists of many producing units of various sizes, highly competitive in character, and surrounded by a number of consulting service organizations, all of which are small. The larger producing companies—and within their resources, the service units also—maintain research laboratories. They tend to be secretive about the developments which take place in these, sometimes to a surprising degree. Hence there is much duplication of effort, particularly in such matters as the design of instruments for geophysical prospecting, and in methods of interpreting the data derived from them.

Number of mathematicians: The industry employs more mathematicians than is generally appreciated, some of them men of very considerable ability. The total of first-rank men is perhaps 15 or 20. Due to the small size of the individual research staffs, however, most of these men carry considerable project responsibility along with their theoretical work. This is the normal state of affairs in small groups: the abnormality is the lack of contact with, and stimulus from, similar men in other companies.

Uses of mathematics: Petroleum research extends in three directions: prospecting for oil, producing it, and refining it.

There are five recognized methods of prospecting: gravity, seismic, electric, magnetic, and chemical. In the first four, important mathematical problems arise in designing sufficiently sensitive instruments and in interpreting data. The fifth requires the use of statistical methods.

Research on methods of producing a field has led to a few mathematical studies of underground flow, and would undoubtedly give rise to others if the results of these studies could be profitably applied. However, since the rate at which oil is brought to the surface is almost entirely determined by law, and the same is indirectly true of well location also, mathematical consideration of the subject is largely sterile, at least so far as American oil fields are concerned.

The third activity—refining—is essentially a chemical industry. Hence the following remarks by Dr. E. C. Williams, Vice President in charge of research of the Shell Development Company, presumably apply not only to the petroleum business, but to manufacturing chemistry in general:

> The two chief problems in chemistry are (aside from the identification on substances): The calculation of chemical equilibrium and the calculation of the rates of attainment of these equilibria. The first problem, involving thermodynamics and statistical mechanics, is rather well understood and usually by very simple computations information sufficiently accurate for industrial application, at least, can be found. Frequently, when several equilibria are possible simultaneously, complicated equations arise, but we rarely solve them directly, but rather set up tables of the dependent variable (the per cent conversion possible) as a function of the independent variables (temperature,

pressure concentration). The sources of these data, however, are numerous and at times require complicated mathematics, as in the calculation of thermodynamic properties from spectroscopic data via quantum statistics.

The situation is much less favorable in the calculation of the rates of chemical reactions. A semiempirical method, based on quantum mechanics, has been applied with a little success to some of the simplest reactions taking place in the gas phase, but virtually no progress has been made in the more important field of heterogeneous reactions (reactions of gases on surfaces, for example). We may say that no satisfactory mathematical theory for such calculation exists at the present time. Some progress is being made, but we are far from being able to predict a suitable catalyst for any desired reaction. For the present we are happy to be able to account for observations made on some simple reactions.

Future prospects: It is inconceivable that research in the industry will not continue at at least its present level. Hence more, rather than less, mathematical work will probably be undertaken in prospecting and in refining. A demand of moderate proportions should exist for able mathematicians with a suitable background of geology and classical physics for the geophysical work, and of physical chemistry and molecular physics in the chemical field.

Aircraft manufacture.—The aircraft industry also consists of a number of independent units, and is highly competitive. It is a new industry in which rapid technical development and rapid increase in size has been the rule. It has depended primarily upon government-supported laboratories and, to a lesser extent, upon the universities for its research, and has busied itself with the exploitation of that research in the advancement of aircraft design. No unit of the industry has had or, for that matter, now has a research laboratory, in the sense in which the words would be used in older and larger businesses, but the beginnings of research departments have appeared, and individual researchers and research projects are clearly recognizable.

Number of mathematicians: Some men in the engineering departments of these companies should undoubtedly be classed as mathematicians, but it is impossible to make even an approximate estimate of their number. It is possible, however, to cite pertinent information which bears on the importance of mathematics to the industry.

The design of a modern four-engine transport plane requires about 600,000 hours of engineering time up to the point where complete working drawings have been prepared. About 100,000 hours are spent on mathematical analysis of structures, performance, lift distribution and stability. Most of this work is routine, but some is fundamental in character, as is evident from several of the examples mentioned earlier in this report.

Of 670 men in the engineering department of one of the larger companies, about 25 have mathematical training beyond that usually obtained by engineers, and 10 or so of these are using this advanced training to a significant extent.

Uses of mathematics: In designing an airplane, five factors are of particular importance. These may be used to indicate the directions in which mathematical research may be expected.

(*1*) *Performance (that is, pay-load, range, speed, climbing rate etc.)*

In the past, forecasts of performance have been based almost entirely on empirical data. Mathematical methods of estimation are now being developed from hydrodynamic theory, however, and are being used to an increasingly greater extent.

(*2*) *Lift and Drag* (*i. e., the force variation over the wings*)

This is the principal objective in the aerodynamic design of the wing. The technique of prediction rests on two supports: wind tunnel experiments and airfoil theory, by means of which experimental data are interpreted and applied. For example, airfoil theory suggests the shape of airfoil to avoid unfavorable pressure distributions and is leading to improved wing sections. This part of aircraft design is already highly mathematical, but a number of fundamental problems still remain unsolved. For example, the theory is still unable to predict stall, and too little is known about optimum shapes or about turbulence, though the recently developed statistical theory of turbulence has contributed to the understanding of the airflow over an airplane and resulted directly in a decrease in airplane drag and consequent improvement in performance.

(*3*) *Stability* (*inherent steadiness of motion*)

The stability of an airplane in flight is inherent in its aerodynamic design and quite distinct from its control or maneuverability. The theory of "small oscillations" has been successfully applied to rectilinear flight. More recently the problem of predicting the response of an airplane to control maneuvers has used the Heaviside operational calculus. Current problems of dynamical stability in which applied mathematicians are interested are the behavior of an airplane when running on the ground and the behavior of seaplanes when running on the water (porpoising).

(*4*) *Structural safety*

Very precise appraisal of structural strength is required in aircraft design. In most industries inaccuracy can be compensated by increased factors of safety, but the pay-load of an airplane is so small a proportion of its total weight that slight increases in factors of safety would seriously reduce its carrying power or even make it unable to get off the ground. Mathematical methods have always been used in this phase of aircraft design in so far as they were available. The standard technique is first to design a part on the basis of calculated strength, then build and test it, and if the tests do not agree with predictions, revise the design and build and test the modified part. This process is continued as many times as necessary to attain a satisfactory result. It is slow and expensive. Theoretical methods are now reliable enough that the majority of structural tests confirm predictions with sufficient accuracy to require no revision. However, new problems constantly present themselves—the introduction of pressurized cabins recently gave rise to several—and hence continual mathematical study is required. A beginning has also been made in the use of the principles of probability in setting up structural loading factors.

(5) *Flutter*

We have already commented upon the impracticability of studying this phenomenon by any means other than the mathematical. The general equations are complicated and have only been solved by making important simplifying assumptions. The results are serviceable for check purposes, but need further elaboration. The importance of the problem increases progressively as more efficient planes are designed, and the necessity for an adequate mathematical theory is becoming critical.

Future prospects: It appears inevitable that from motives of economy the industry will rely increasingly upon theoretical methods of design and that mathematics will play a larger part in the future than at present. It is also probable that for competitive reasons the various companies will supplement government research by fundamental studies of their own. Furthermore, in view of the present fragmentary state of aerodynamic theory, it would not be surprising if part of the research effort was devoted to the improvement of the basic theory itself.

The reliability of these predictions is, of course, conditioned by the financial prospects of the industry. Just now, war orders are causing abnormal inflation of earnings; when these cease, retrenchment will be inevitable. The industry is not highly mechanized, however, and hence its present cycle of inflation does not imply so large an expenditure for plant as would be true in most manufacturing fields. For this reason, the period of deflation may prove to be one of large war profits in the bank but insufficient orders to occupy the time of many competent technical men whom the management would be reluctant to let go. If this should occur, an almost explosive development of research may take place.

Whether the development is explosive or not, however, it is probable that the industry will soon become one of the largest employers of industrial mathematicians.

Industrial Statistics and Statisticians

The subject of statistics enters the business world at points quite distinct from those touched by the rest of mathematics. Moreover, the types of business activity to which it most frequently applies—insurance and finance, economic forecasting, market surveys, elasticity of demand against price, benefit and pension plans, etc.—belong to the field of economics which is the subject of a separate report, and need not be touched on here.

There are certain other respects in which statistical theory could be of great service in industry, but they have been exploited to only a limited extent. This report must therefore point out these hopeful fields rather than record achievements in them.

Statisticians in Industry

By "statistician" we mean a person versed in and using the mathematical theory of statistics, not one who collects, charts, and scrutinizes factual data. In the business world the word is more often used in the latter sense.

There is a very great difference between the number of statisticians in industry, and the number of men interested in some form of statistics. How great the discrepancy is will be clear from a comparison of the membership of the American Statistical Association, which devotes itself to the application of statistics in its broadest sense, and of the American Institute of Mathematical Statistics, which confines itself narrowly to the development of statistical technique. The former lists 277 names with industrial addresses; the latter only 10.

Statistics in Industry

Dr. W. A. Shewhart, research statistician of the Bell Telephone Laboratories, has delineated broadly and succinctly the field in which statistics may be expected to find application as follows:

> Since inductive inferences are only probable, or, in other words, since repetitions of any operation under the same essential conditions cannot be expected to give identical results, we need a scientific method that will indicate the degree of observed variability that should not be left to chance. Hence it appears that the use of mathematical statistics is essential to the development of an adequate scientific method, and that mathematical statistics may be expected to be of potential use wherever scientific method can be used to advantage.

More specifically, there are five recognizable types of industrial engineering activity in which statistical theory either is, or should be used.

(*a*) In studying experimental data to determine whether the observed variations should be regarded as accidental or significant. An example is found in the field of geochemical prospecting. The surface soil overlying regions in which there is oil contains a higher proportion of hydrocarbons and waxes than occur in other locations. Chemical analysis of surface soil therefore affords a means of prospecting for oil. Mr. Eugene McDermott writes:

> In the geochemical method, it was found necessary to determine between samples showing significantly high analysis values, and those which were normal values. These normal sample values, of course, had considerable variation between themselves, due to analysis and in larger part sampling errors. After examining these data for a long period of time, it was decided to approach the problem statistically. This disclosed at once that areas surveyed could be divided into positive (having significant values, and hence favorable from the standpoint of petroleum possibilities), negative (no significant values and unfavorable for petroleum) and marginal (indeterminate). The latter case is always the most difficult one in surveying, and while we are now able to recognize it, further work is needed to fully interpret it. This kind of mathematics is being applied at the present moment, and bids fair to solve the problem.

(*b*) In planning the kind of experiments from which such data arise. Whether variations are or are not significant depends in no small degree upon the fashion in which the data were taken. Consideration of the experiment in advance from a statistical point of view often results in economy of procedure, or even points the difference between a trustworthy and a meaningless result.

The following example is quoted from an address by Dr. R. H. Pickard, Director of the British Cotton Research Association:

> To illustrate the advantage of good experimental design I may refer to some experiments carried out at the Shirley Institute to find the effect of various treatments on a quality of cloth. This quality varies considerably at different parts of the same piece of cloth, and in order to measure the effect of the treatments the tests are repeated systematically so that the variations are "averaged out." Some of the natural variation, however, is systematic, and by adopting a "Latin Square" arrangement of treatments on the cloth (such as is much used in agricultural yield trials), these systematic variations are eliminated from the comparison, and in the instance quoted the result was to reduce by one-half the number of tests necessary for a given significance as compared with a random arrangement.[8]

To the extent to which biology becomes an important element in industrial research—and it would appear to be on the point of doing so in such fields as food manufacturing—it can be expected that the type of statistical work listed under (*a*) and (*b*) will rapidly increase.

(*c*) In laying out an inspection routine. Manufacturing inspection frequently yields data which are best interpreted statistically, either because only spot-checks are taken, or because the method of inspection gives measurements which are themselves subject to accidental fluctuation. In such cases statistical theory is of great advantage in setting up an effective and economical inspection program. It is being so used in certain industries, notably in electrical manufacturing and textiles, but the potential field of usefulness is far from covered.

The following example is quoted from an address by Mr. Warner Eustis, staff officer on research of the Kendall Company:

> Surgical sutures are twisted strands of sheep intestine, which has been slit lengthwise * * * After a stated number of days a sewing with such material, implanted in the body during a surgical operation, will be digested and disappear as the healing processes progressively take up the load originally held by the suture * * * Here is a product which it is impossible to test in any way without destroying the product, especially as each suture is sealed in an individual, sterilized tube. Our final product tests must all be conducted by breaking open a sterile tube and testing the product therein. The quality appraisal of such a product naturally rests upon probability, rather than upon an actual testing of each item. Due to the nature of such a product, in which a single failure may destroy human life, the need for accurate quality appraisal is superlative.[9]

(*d*) In the control of manufacturing processes. Inspection is not merely a means of discarding bad product; it is also a means of detecting trouble in the factory. This is obvious in the extreme cases when the product is unusually bad. By the use of suitable routines set up in accordance with statistical theory, the day-to-day results of inspection can be used to detect incipient degradation in the process of manufacture which might otherwise escape notice. This procedure is used extensively by the Western Electric Company in assuring uniform quality in many items of manufacture, and to a lesser extent in other industries. Of it, Mr. J. M. Juran, manufacturing engineer of the Western Electric Company, says:

> Too frequently we have seen an inspection group grow lax in vigilance until a complaint from the customer wakes them up. They promptly swing the pendulum a full stroke in the opposite direction, and the factory groans in its effort to meet the now unreasonable demands. A sound and steady control, like a sound currency in commercial relations, gives factory foremen a feeling of confidence and gives the consumer a feeling that control is being exercised before the product reaches him.[10]

(*e*) In writing rational specifications. Obviously, if such a procedure helps the manufacturer to assure uniform quality, it is also of value to the purchaser of his products. Hence the subject of statistics enters into the writing of the buyer's specifications. It has been so used to a limited extent in the Bell System in connection with telephone apparatus, and by the United

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[8] Pickard, R. H. The application of statistical methods to production and research in industry. *Journal of the Royal Statistical Society, Supplement, 1*, No. 2, 9–10 (1934).

[9] Eustis, Warner. Why the Kendall Company is interested in statistical methods. *Industrial Statistics Conference, Proceedings*, 143–144 (held at Massachusetts Institute of Technology, Cambridge, Mass., September 8–9, 1938).

[10] Juran, J. M. Inspectors' errors in quality control. *Mechanical Engineering, 57*, 643–644 (October 1935).

States Government in the purchase of munitions. However, it must still be rated as a relatively undeveloped field. Of it, Captain Leslie E. Simon, Ordnance Department of the United States Army, says:

> Statistical methods have proved to be a powerful tool in the critical examination of some ammunition specifications prior to final approval. Their use, either directly or indirectly, is almost essential in determining a reasonable and economic standard of quality through the method of comparing the quality desired with that which can be reasonably expected under good manufacturing practice. In like manner, the statistical technique renders a valuable service in framing the acceptance specifications. Through its use the quantity and kind of evidence which will be accepted as proof that the product will meet the standard of quality can be clearly expressed in a fair, unequivocal, and operationally verifiable way.

Conclusion

It is perhaps unusual to conclude a survey of this sort by stating the impressions which it has made upon its writer. In the present instance, however, the element of self-education has been so large that these impressions may summarize the report better than any more formal recapitulation. They are:

(1) Because of its general significance as the language of natural science, mathematics already pervades the whole of industrial research.

(2) Its field of usefulness is nevertheless growing, partly through the development of new industries such as the aircraft business, and partly through the incorporation of new scientific developments into industrial research, as in the application of quantum physics in chemical manufacturing and statistical theory in the control of manufacturing processes.

(3) The need for professional mathematicians in industry will grow as the complexity of industrial research increases, though their number will never be comparable to that of physicists or chemists.

(4) There is a serious lack of university courses for the graduate training of industrial mathematicians.

(5) Management, which is already keenly alive to the importance of mathematics, is also rapidly awakening to the value of mathematicians and the peculiar relationship which they bear to other scientific personnel.

This last observation is not trivial. There was a day when, in engineering circles, mathematicians were rather contemptuously characterized as queer and incompetent. That day is about over. Just now, an attitude more commonly met is one of amazed pride in pointing to some employee who "isn't like most mathematicians; he gives you an answer you can use, and isn't afraid to make approximations." As the proper function of the industrial mathematician becomes better understood, these proud remarks will no doubt cease. Those who are adapted to the job will be taken for granted; the others will be recognized as personnel errors and not mistaken for the professional type. Perhaps the present report may speed this day. If so, it will have been a service to the profession and to industry.

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SECTION VI

5. METALLURGICAL RESEARCH AS A NATIONAL RESOURCE

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ABSTRACT

Metals are necessary to every industry. Implements for agriculture, machines and tools for manufacturing, reaction vessels for chemistry, all the means of transportation, trains, trucks and passenger cars, planes, steamships, electric power lines, the telephone and telegraph, the printing press, household furnaces and stoves, gas and water piping, electric lights, the tin cans on the pantry shelf—indeed anything one cares to name—relies directly or indirectly upon metals.

The welfare of the ultimate consumer demands that metals and alloys of suitable properties and reasonable cost be supplied to meet present needs and, when different properties or further reductions in cost are called for to meet new needs or changing economic conditions, that no stone be left unturned to fill the needs.

The metal-producing and metal-using industries have filled present needs and are preparing to meet new ones through research, carried on from the urge of the profit motive. Fruitful metallurgical research could be cited that would fill many volumes. A few cases, selected as representative, are mentioned in connection with aluminum, copper, zinc, magnesium, corrosion-resistant steels, high-speed and cemented-carbide tools, railway rails, continuous rolling of flat steel products, that have brought benefits to the ultimate consumer, created employment, and provided funds for the tax gatherers.

It is characteristic of metal-producing industries that quantity production is essential for economy. This requires huge expenditures of capital for plant and equipment. Large, strongly financed firms, in some special cases even quasi monopolies, are the rule. Such firms take a long view; they plan for their future existence. They consider it as necessary to insure a steady flow of technological improvements in products and processes, and the development of entirely new products, as it is to arrange for ample supplies of raw materials. Hence well-manned and well-equipped research and development groups are an essential part of the corporate set-up in all major metallurgical industries. The utilization of research has not yet proceeded so far in those industries as in the chemical industries, but the rate of increase in metallurgical research has been rapid in the last decade, and shows no signs of slowing up.

The research laboratories of the metallurgical industries are operated on a teamwork basis and advances are made nowadays on the basis of intensive work of a group rather than by the sole effort of a lone investigator. This trend extends beyond the confines of a single firm, in that secrecy is at a minimum and free exchange of information at a maximum.

Several strong technical societies, other special groups organized for interchange of information, and the trade and technical metallurgical journals provide means of disseminating and reaping information. To this situation may be ascribed the fact that metallurgical research workers are recruited not only from students of special metallurgical courses in the universities, but equally from the ranks of physicists, chemists and engineers who have a scientific foundation from their college course and superimpose on this, by their own study of the available metallurgical literature, the requisite specific metallurgical information.

Thus the will to carry on continuous research exists in, and a supply of qualified personnel for research is available to, the metallurgical industries. As appreciation spreads of the necessity for research, many companies already engaged in research find special metallurgical research problems cropping up that are outside the range of experience of their own staff and for which equipment is lacking in their own laboratories. Similarly, firms, especially among users of metallurgical products, not yet able to finance permanent research staffs and equipment are faced with the problem of finding means for the solution of the problems. If the problem is common to a number of firms, they may pool their interests and engage in joint research, often through the instrumentality of a committee of a technical society. Such joint problems, as well as the individual problems of the single firms referred to above, have to be farmed out to laboratories staffed and equipped for metallurgical work. Such laboratories, established as engineering experiment stations of universities and as specialized research institutes, are extensively utilized. Conditions, therefore, are favorable for the continual flow of research required for the metallurgical needs of the nation.

Scope of Metallurgy

Advancement in metallurgy is important, not only to the industries that are recognized as primarily metallurgical, but to every industry, for all industries depend upon metals, either directly as forming a part of the product, or indirectly in the form of machinery and tools, or still more indirectly, in transporting raw materials and finished products.

The modern airplane is the result both of research in aerodynamics and the like and also of research on materials of construction. In the engine, many metals are used the successful extraction of which from the ores, as well as their purification, alloying, heat treatment, and even their machining to size, are the fruits of long-continued research by many individuals and organizations. In an airplane itself the materials are largely chromium-molybdenum steel and strong aluminum alloys, with stainless steel as a possible alternative for the latter.

The automobile likewise calls for a variety of alloy steels; for nonferrous alloys in bearings, radiator, storage battery, head lamps, cylinder heads, etc.; for cast iron for cylinder blocks and braking surfaces, special alloys for pistons, wide steel sheets of high formability and suitable weldability for the body, zinc-base die castings for the grilles, and stainless or chromium plated steel for hub caps and trim. All these various metallic materials are chosen for their particular combinations of mechanical properties, reliability, cheapness, formability, machinability, appearance, and so on. Among the paramount characteristics of materials for low-cost production are the ability to be formed and machined readily. Likewise, effective forming equipment and cutting tools are required. In assembly, rapid welding is almost as important as are machining and grinding for bringing pieces to the required dimensional limits. In inspection for that dimensional accuracy, which permits the use of interchangeable parts, gages that are wear-resistant and metallurgically stable in their own dimensions, are prerequisites.

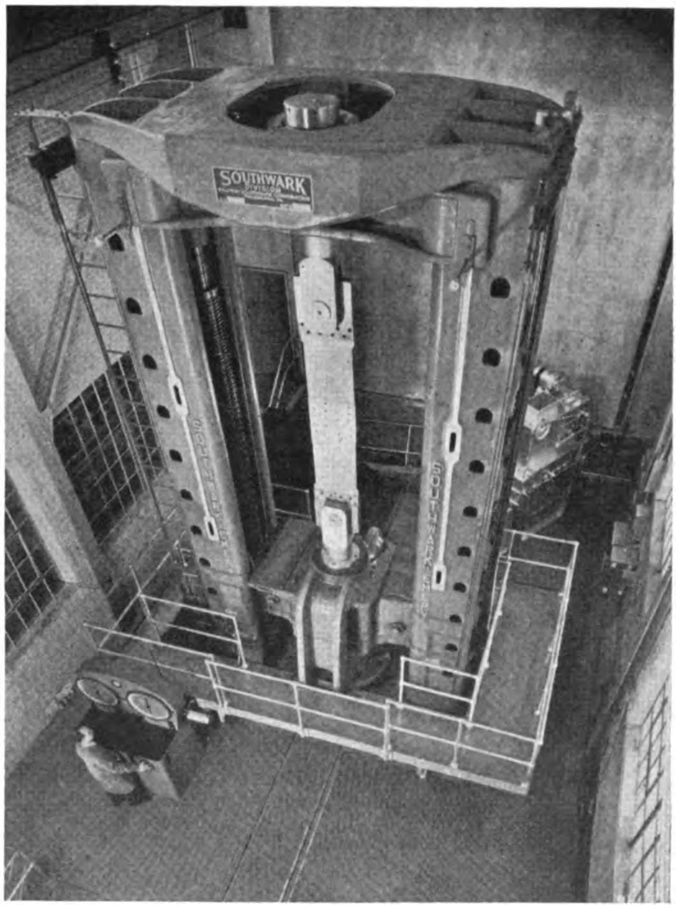

FIGURE 89.—Templin Precision Metal Working Machine, Aluminum Research Laboratories, Aluminum Company of America, New Kensington, Pennsylvania

The railroads need rails and wheels that will not fail in service and materials for car construction of high strength-weight ratio that afford safety with minimum dead load and maximum pay load. Marked advances have been made in providing metallurgical products that fill these needs.

The electrical industry has succeeded in halving the coal required per kilowatt-hour as compared with requirements of about a decade ago, and in vastly increasing the illumination produced per kilowatt from electric lights in about the same period. Steels that permit the boilers and turbines to operate at higher temperatures and pressures were essential in the one case, ductile tungsten in the other

Advances in the chemical industry bring increased demands on metallurgy for materials of construction that combine the other necessary properties with corrosion resistance under many unusual and difficult conditions. Other industries the final products of which are wholly nonmetallic, such as the lumber, paper, textile, plastics, glass, and ceramic industries, require metals with special characteristics for saws, calendering rolls, Fourdrinier wires, sulfite digesters, looms, rayon spinnerets, molds, furnace parts, and so on. Anything made by machinery indirectly requires that there be metals in the machines and metal-cutting tools for making them. Modern agriculture must have tools, tractors, and other machines for tilling, cultivating, and harvesting. The food industries require metals in their processing equipment as well as tin cans to hold the product. Road making calls for rock crushers, and so on. All the transportation industries, the petroleum industry, the electrical industry, indeed, any industry you care to name, vitally depends on metallurgy.

Economic Consequences of Metallurgical Research

The service and satisfaction to the public provided by the products of metallurgical research which meet the varied requirements of all these industries, the employment given in their manufacture and servicing, the taxes paid to government from the new or rejuvenated industries thus made possible, and the conservation of natural resources secured by fitting the materials to their jobs and taking less and less material to do the same work, are apparent to any thoughtful observer.

It is essential to the national economy that the stream of technological progress flows freely. Engineering advances cannot go far without simultaneous or preceding advances in creating new metallurgical materials. Metallurgical research is an essential national resource, because technological advances do not just happen automatically; they have to be produced deliberately. The results are manifold. To pick an example from the metallurgical industries, the development of aluminum from the position of a chemical curiosity, rarely seen outside of museums, to that of an everyday material of construction for utilitarian service in pots and pans, in gleaming transport planes, in streamlined railway coaches and in multitudes of applications more familiar to the engineer than to the public, did not just happen by itself. This development has been the fruit of research. Research has built the American aluminum industry from the very first day when the young student, Hall, who knew very well just what he was seeking, made his first few pellets of the metal, on through the early days when it had to sell for $5 per pound, through the period during which its utility was demonstrated, to the consequent building up of a demand that led to large production and thereby to a steady lowering of its cost, until it now sells at 17 cents per pound. In this development there has been created a huge industry that gives employment and provides funds for the tax gatherer. Employment is created and taxes are paid, not only by the aluminum industry itself, but also by the aircraft industry (which would have difficulty in making planes of requisite strength and lightness without the strong, light aluminum alloys), and by every other user of aluminum.

Nor did the aluminum industry discontinue research once a market was established. The competition of other metals demands continuous research which is being carried on upon an ever expanding scale. A recent statement by the President of the Aluminum Company of America[1] says that no increase[2] in the price of aluminum to domestic customers is contemplated because the "benefits of research and development permit the company to expect lower costs and it intends to share such economies with consumers of aluminum." This published statement is significant because it shows that the management is aware that the public understands research, appreciates its possibilities, and values its results. It was not necessary to append a footnote defining research.

Group vs. Individual Research

The common metals are used widely not only because of their properties, but equally because of their reasonable cost. To attain reasonable costs, quantity production and a very high investment in equipment are generally necessary. Units in the metallurgical industries are therefore likely to be large and to require ample financing. To develop, test, and install the production equipment necessary for the fruition of a research idea in the metallurgical field is, in these days, seldom within the means of an individual. Capital must, therefore, be attracted or, conversely, industries already capitalized must do research for themselves and on their own problems. One has to go a long way back in the metallurgical industries to find an analogy to Goodyear's kitchen-stove laboratory, and to his own production and sale of raincoats to get funds for the further investigation of rubber and the development of its other uses.

Perhaps the closest analogy in metallurgy goes back to the case just mentioned of Hall who, while a student in chemistry at Oberlin, carried out, as an extracurricular activity, individual, very small-scale experiments on the production of aluminum, succeeded in attracting capital, and established the basis for the American aluminum industry. It is a far cry indeed from that

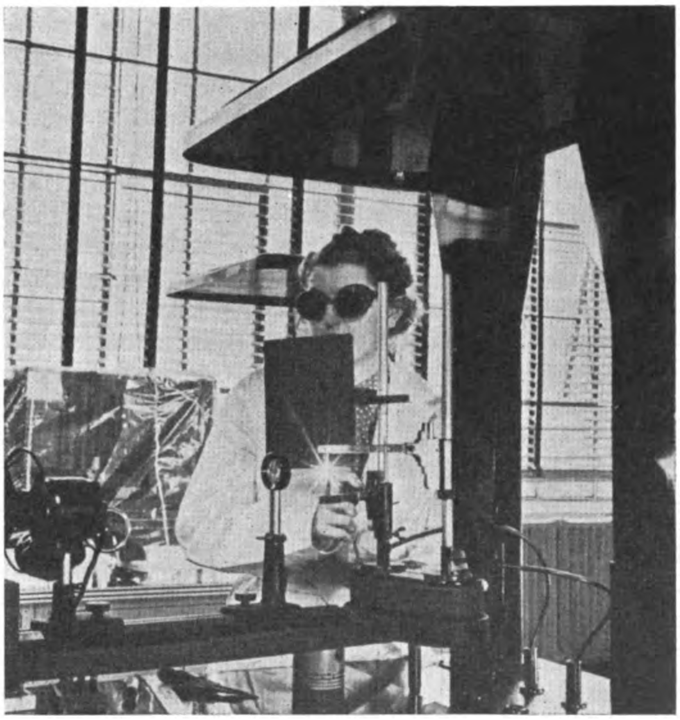

FIGURE 90.—Spectroscopic Examination of Metals, Chrysler Corporation, Detroit, Michigan

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[1] To share economy. *Automotive Industries*, 81, 643 (December 15, 1939).

[2] The price was, in fact, reduced early in 1940 and again in the fall.

individual research effort and its crude equipment to the community of effort, the large personnel, and the specialized equipment and facilities of the research laboratories of the Aluminum Company of America today, and the pilot-plant set-up required to translate the resultant research findings into practice.

Whereas the large, strong organization can finance long-term projects, can bide its time to utilize the results, and can insure, by sheer number of the investigations in hand, that some few of them will prove money makers in time, the small firm must have more immediate results. Conversely, the small firm is usually in competition with a smaller number of other firms (because it usually markets its products within a smaller area), and is more flexible in its ability to install an improvement promptly. The small firm may not be justified in building up a research staff of its own with the equipment necessary for effective work. Here a qualified consultant, an engineering experiment station, or an independent specialized research laboratory, may be of service in providing the fundamental information, and the impartial viewpoint that the small organization often lacks, and may supplement these by whatever measure of experimental work the specific problems demand and justify. There are free-lance metallurgists who came up through the ranks in laboratories engaged in group research who now act as consultants. Laboratory facilities and other men to use them must be provided by the client to put the research suggestions of such free-lancers into effect. Because of the thousands of plants engaged in making products out of metals, this problem of how the smaller unit may enjoy the fruits of research is even more pressing than it is in most fields outside of metallurgy.

In view of the trend toward group attack on metallurgical research problems, it may be asked whether the individual investigator has become extinct. He is becoming more rare, but is far from extinct. The writer recalls with interest witnessing early experiments on the manufacture of steel automobile brake drums centrifugally lined with wear-resisting cast iron, carried on by an experimenter whose colleagues called him "Angle-iron Joe." This was because he would not wait, when struck with an idea, to have the drafting room design and the machine shop construct his apparatus, but would himself put together, from angle iron and whatever else was handy, equipment that would serve, and serve promptly, while the idea was hot, to tell him whether it had merit. Within a period that was amazingly short as most research projects go, Joe had evaluated the compositions, temperatures, speeds, and fluxing operations necessary for good bonding and for the desired metallographic structure, and was able to direct the draftsmen and mechanics in the construction of apparatus which went into successful commercial production. The method and the product are now standard. The development was put into immediate use by Joe's employer, but the initial demonstration was sufficiently convincing that, had he been a free lance, it would not have been difficult to find backing.

Lessons From the Past

The problems of how to insure that the stream of metallurgical research shall continue to flow in steadily increasing volume is not different in principle from the broader one facing research in all industry. We may expect to find the same general pattern for successful research in every industry. However, there has been enough experience with metallurgical research to make a few of its case histories and certain generalizations drawn therefrom worth considering here. The successful research of the past should point the way for research of the future.

Machining and Machinability

As epoch-making a metallurgical research project as has ever been carried out was that of the engineers Taylor and White, who, with research equipment advanced for its day, but so crude in the light of modern practice as to make one wonder how they made it work, developed for the Bethlehem Steel Co. tungsten high-speed steels not very different from those used today, and thereby revolutionized the art of cutting metals. What this has meant in terms of increased machine-shop production and lowered cost is simply incalculable.

So vital did high-speed tools become in the manufacture not only of peacetime products, but also of munitions, that tungsten became a strategic material and its domestic scarcity and the necessity for its importation became matters of great military concern. However, domestic molybdenum had meantime appeared on the scene. Its economical production from the huge deposit of ore low in molybdenum would, in earlier days, have been very difficult, but it was actually made easy by virtue of previous research on the flotation of copper ores. The flotation process had been the key to the utilization of the great deposits of lean porphyry copper ores, and to the maintenance of copper in the class of relatively cheap metals despite the depletion of rich ores. This also is a dramatic story in itself. Interestingly enough, these lean copper ores themselves contain molybdenum, though it occurs only to about 1 one-hundredth to 5 one-hundredths of 1 percent of the weight of the ore, and its presence was for a long time unsuspected. The application of selective flotation, a further development of research, now makes these lean copper ores an important source of molybdenum as a byproduct.

Some early experiments made in England while molybdenum was a "rare" and expensive metal, coupled with the chemical and metallurgical similarity of tungsten and molybdenum, suggested the use of molybdenum as a substitute for tungsten in making high-speed steel. Research at Watertown Arsenal, undertaken from the strategic-materials point of view, showed it to be more potent than tungsten in high-speed steel, weight for weight, and when "bugs" cropped up due to certain idiosyncrasies of the molybdenum steels, these accessory problems, too, were solved. Coincidentally, research on molybdenum steels for automotive and aircraft use had developed such properties and created such a demand for the metal that its production had risen and its price had fallen to a point where it was cheaper to make a tool steel with molybdenum than with tungsten, though the demand for tool steel alone would not have produced a great volume of production or a significant drop in price. Foreseeing this situation, metallurgists who made tools and tool steels stayed with the problem of overcoming the difficulties and utilizing the advantages. As a result molybdenum high-speed tools are proving so satisfactory that there is today no apprehension whatever about a wartime shortage of tungsten. Indeed, molybdenum itself is among the materials that Americans are requested not to export to nations that practice aggression against weaker nations and bomb noncombatants. Research has shifted the situation from one where only 10 years ago[3] our lack of tungsten was a serious strategic liability to one where our abundance of molybdenum is a strategic asset.

Nor did research on cutting tools stop there. Cemented carbides of tungsten, tantalum, and the like have been developed, by long and patient research backed by ample capital, into tools the cutting power of which surpasses that of high-speed steel tools as much as those surpassed the carbon-steel tools. In consequence materials formerly classed as nonmachinable, even with high-speed tools, now are cut readily. As for materials still untouchable by the carbide tools, we have artificial abrasives developed by electrochemical research, and marvelous machine tools for machining by grinding, which make it feasible to shape almost any metallic product, no matter how hard it may be.

Not only has research developed the cutting tools, but the metals to be cut have been modified, without much sacrifice of essential mechanical properties, so that they may be more readily machined. Beside the older free-cutting steels and leaded brasses, we now have stainless steel plus selenium, copper alloys plus tellurium, aluminum alloys with a variety of additions, and recently carbon and alloy steels plus lead, each of which additions increases machinability, often without material sacrifice of mechanical properties.

Every one of these developments in machining and machinability, outside of the work of Watertown Arsenal, was carried out by private capital for the ultimate purpose of private gain, and all utilized the brains of many research workers and the best of modern equipment. Many of the projects were costly to carry out and quite beyond the scope of the average individual investigator unable to command ample research facilities, and equally beyond the scope of most university laboratories.

Joining of Metals

Second only in importance in fabrication to the machining of metal parts is their joining. Welding has grown from a rule-of-thumb operation employed for unimportant joints, to one that can be, and often is, of hair-trigger accuracy, controlled by devices of great precision, for example in the assembly of automobile bodies. Welding of rails into long lengths, of ships, of structural steel (with avoidance of the noise of riveting), of jointless pipe lines, of airplane-engine supports, and of fuselage and wing structures is a commonplace today. Even the welding procedures still carried out by hand are systematized, the workmen being carefully chosen, trained, and tested for ability, and the welds subjected to X-ray and other tests to insure soundness.

Hand in hand with the mechanical developments in all the dozen or more different welding methods has come a recognition of the metallurgical principles involved, the development by metallurgists of steels suitable for welding, and of fluxes and fluxing methods, all to the end that reliable welds may be made consistently. Mechanical, electrical, and metallurgical engineers have all cooperated in these advances.

Another important method of joining is by copper brazing in some suitable reducing atmosphere. This, and the analogous processes of bright annealing and clean hardening of steels in controlled atmospheres, have been developed through the joint efforts of the chemist and the metallurgist.

Still another valuable means for joining a wide variety of alloys is the relatively new family of silver solders, materials characterized by ease of application, joint strength, and ability to withstand elevated temperature. The expense of using silver as an important constituent of the solder is fully justified.

Outstanding Work in the Steel Industry

Since steel is the most important member of the family of alloys the bulk of metallurgical research relates to steel.

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[3] Taylor, R. Strategic raw materials. *Metals and Alloys*, 1, 5 (1929).

Continuous Rolling

The development of the continuous rolling mill for the steel industry was a successful and profitable undertaking, which has materially reduced the cost of flat steel products to the ultimate consumer and greatly extended their use. The work (which involved more mechanical and electrical than strictly metallurgical research) necessary to bring this idea to its present position, probably comprises the most expensive research project ever undertaken in the field of metals.

To one acquainted with the old-time method of rolling, with its many roll stands, great amount of back-breaking handling of materials, and dependence upon the roller's judgment, not to mention the irregular quality of the products, the modern continuous mill with its few stands but its myriads of precise controls, and the uniform quality of the product, is a revelation indeed. When these mills were under erection, there were dire prophecies of overcapacity. The judgment of steel industry executives that a better and cheaper product would find new uses has been abundantly justified. Every home now has conveniences it did not have in earlier days, the availability of which, at a price justifying their purchase, can be traced to the availability of good, cheap, flat-rolled steel as raw material. The sum total of employment resulting from the change in practice is also undoubtedly on the right side of the ledger.

Continuous Tubing

Even before this continuous-rolling development an analogous one was getting started in the production of welded tubing. A tiny plant worked out a method for drawing heated flat stock, "skelp," through sets of rolls in such fashion as to cause the edges to weld, and to subject the weld to mechanical working. First developed for very small sizes of tubing, it was found to give very clean welds, to be susceptible of accurate control and hence to be suitable for handling long lengths. That is, the process can use the long coils of flat stock produced by the continuous rolling process so its development was favored by the recent availability of suitable stock.

Over the last 20 years the process has been improved, adapted to fairly large sizes, and implemented with suitable equipment and control devices, until it has made large inroads upon the older method of pulling the skelp through a bell to force the edges into welding contact. Many of the larger producers of tubing have changed, or are changing, to the process. This is true not only in the United States, but all over the world. The original tiny plant with its handful of men and small production, something like an experimental pilot plant of today, has flowered amazingly. The "big fellows" accepted a scheme worked out by a "little fellow." This shows that the lone inventor still has a place. In this case the inventor was fortunate in being able himself to enter production and demonstrate the virtues of the product by its salability in a competitive market.

Continuous Forming From the Melt

Efforts are being put forth to carry the idea of continuous forming to its logical conclusion by starting with molten metal continuously cast as a strip or a rod, and processing it to thinner strip or to wire without interruption. Plenty of difficulties still beset these efforts. One cannot yet evaluate them on the basis of fully proven achievement, but they do show promise of improvements to come that may be as revolutionary as was the continuous mill.

Raw Materials

Research in the utilization of the raw materials of the steel industry has not been neglected. In blast-furnace practice research has produced notable results in the use of lower grade iron ores, reduction in coke consumption, and the production of a more uniform product. In basic open-hearth steel making the results obtained during the last 20 years have been amazing in the conservation of fuel, in greater production, and above all in the improvement of quality. A very noteworthy instance has been the study of open-hearth slags and the application of the principles of physical chemistry to the process. It has been research work of the best kind.

Research in the field of molding sands has been very fruitful in foundry practice, and the resultant savings to the foundry industries have been very large, to say nothing of the assurance of more uniform and better quality of castings.

Research in the refractories industries has been very helpful to the metallurgical industries, and in many cases has been carried out because the iron and steel and other metallurgical industries asked for better refractories.

The iron and steel industry is "research minded." The men in charge of production are never satisfied. They constantly seek for more and improved products. Every time a blast furnace or open hearth is rebuilt something new is tried, sometimes along radical lines. This attitude of mind is an enormous national resource.

New Viewpoints

Possession of the research point of view is a precious possession. It steers one's mode of thinking into new channels, leading to new seas and new lands of research advances whose existence was hitherto unsuspected. Thum [4] comments that some recent outstanding met-

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[4] Thum, E. E. Editorial—Where do we go from here? *Metal Progress*, 32, 643–49 (November 1937).

allurgical advances violate established concepts so grossly as to appear, at first sight, to run counter to fundamental laws. He says that really fundamental advances are likely to come when someone pulls his mind out of the rut that every other mind is following and goes off in an entirely different direction. The research-minded man is far more likely to jump out of the rut than is the production-minded man.

An example of this is the shift in the classification of phosphorus in steel from the category of a poison, to that of a tonic, as Sauveur [5] phrased it. In the very early days of steel, high-phosphorus steels, in which experience dictated that the carbon must be low, were in use, because it was not known how to remove phosphorus. But as advancing technology made it more feasible to lower the phosphorus content, and since high phosphorus causes embrittlement in the presence of too much carbon, practice and specifications changed to limit that element to the lowest practical level.[6]

Copper and Phosphorus in Steels

Some 25 years ago a committee of the American Society for Testing Materials undertook research on the resistance to atmospheric corrosion of steels of varying copper content. This was done because of a controversy between two factions of metallurgists, one advocating a copper content of some 0.20 percent, the other advocating "extreme purity," i. e., avoiding all copper as nearly as possible. The experimental method was adopted of exposing a large number of sheets of known composition at a number of different locations and observing their resistance to the elements year by year. The experiment took years for completion. Not only was it made evident long before all the sheets had rusted through that copper was a help, in resisting the effects of such exposure, but Storey,[7] taking the phosphorus content into consideration as well, pointed out that it also was helpful.

Much later in the search by research men for still better corrosion resistance of bare steel in the atmosphere, primarily from the point of view of roofing materials, it was found that a low-carbon steel with the phosphorus shockingly high according to ideas then prevalent, plus copper and small amounts of other alloying elements, not only had somewhat improved corrosion resistance, but a yield strength double that of ordinary structural steel, plus satisfactory formability and weldability.[8] Furthermore this was all accomplished at a very low cost for alloying elements and without any need for heat treatment. The suitability of such steel for bridges, ships, railway cars, truck bodies, and so on was obvious. A score of other steels of equal yield strength and good corrosion resistance, some containing more expensive alloying elements without phosphorus, others containing phosphorus and still cheaper ingredients as alloying materials came on the market in quick succession to fill a real need and form a brand new class of structural steels.[9]

Once an erroneous belief is wiped out by some bold research worker, a long train of industrial consequences is likely to result, involving many other experimenters.

Stainless Steels

Another case of a long train of experiment is the recent, but well-known stainless steel, 18:8, containing 18 percent of chromium and 8 percent of nickel, the research development of which, along with that of the plain chromium stainless steels, it would be interesting to trace in detail were space available, since their corrosion resistance and mechanical properties make them extremely serviceable for a wide range of corrosive conditions. It is commercially too expensive to make 18:8 with a very low carbon content i. e. less than about 0.06 percent. In welding 18:8 containing even this small proportion of carbon, an embrittling separation of carbides occurs as the metal cools from the welding temperature by a precipitation phenomenon akin to that which occurs in the heat treatment of duralumin. To prevent this an element is added that will form a more stable carbide and one less prone to dissolve and precipitate in this fashion; molybdenum (the presence of which is also helpful in resisting some special conditions of corrosion) is useful and titanium and columbium are especially potent. The addition of titanium or columbium was the direct result of logical thinking about the phenomena concerned, but their effectiveness had to be proved by exhaustive experiment. In the case of columbium, the world had to be scoured for ores of this then rare metal to make sure that an adequate commercial supply would be available. This was no task for an individual researcher not backed by ample funds.

Clad Metals

Once the technical value of the 18:8 type of steel became established, the economic angle appeared. On the basis of "save the surface, you save all," many began to ask whether a thin skin of stainless would not suffice and whether a "clad" material, ordinary steel with a mere film of stainless on the surface, could

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[5] Sauveur, A. A review of progress in ferrous metallurgy. *Steel, 99*, 38 (July 6, 1936).

[6] Gillett, H. W. Phosphorus as an alloying element in steel. *Metals and Alloys, 6*, 280, 307 (1935).

[7] Storey, O. W. Discussion (Corrosion resistance of steel). *Transactions of the American Electrochemical Society, 39*, 121 (1921).

[8] Epstein, S. J., Nead, J., and Halley, J. W. Choosing a composition for low-alloy high-strength steel. *Transactions of the American Institute of Mining and Metallurgical Engineers, 120*, 309 (1936).

[9] Lorig, C. H., and Krause, D. E. Phosphorus as an alloying element in low carbon, low alloy steels. *Metals and Alloys, 7*, 9, 51, 69 (1936).

not be developed. Alclad aluminum, a similar product consisting of a strong aluminum alloy base carrying a pure aluminum surface had previously been developed and found wide use in aircraft.

The cost of the cladding process proved so high with 18:8 that the expected margin of saving was difficult to attain, but effort is being continued with signs that ultimate success may be in sight.

Hydrogen in Steel

Failure through transverse fissures of rails in railway service has caused bad wrecks and given railroad executives much cause for worry. Means were developed for detecting fissured rails in track and removing them before failure, but this was cure rather than prevention. The source of fissures was long in dispute but is now regarded as preexistent internal shatter cracks formed as the rail cools after hot-rolling. Certain slow cooling schedules have been found to prevent cracking and are applied commercially to almost all rails. It is now evident that the presence of hydrogen fosters cracking and means to insure its absence are being sought.

The Rare Elements Put to Use

Even in the limited number of cases mentioned above, from the hundreds of equal import that could be cited, the elements molybdenum, tantalum, selenium, tellurium, beryllium, titanium, and columbium have been mentioned as alloying elements commercially utilized in steel, each of which does a specific job excellently. There is also hydrogen which is, in the case cited, harmful. Ten years ago a book on metallurgy written from the point of view of commercial practice would have omitted all these elements save molybdenum, and one of 15 years ago would very likely have omitted that. The metallurgist of today recognizes that there doubtless are no useless or ineffective elements, and that, as in the instances cited of phosphorus and lead in steel, even the familiar ones may at any time turn up in a new role.

Nonferrous Examples

While one naturally picks the steel industry to supply outstanding examples of successful research, case histories are not lacking in the nonferrous industries.

Zinc

Zinc is a cheap metal. On a volume basis, it is a very cheap metal. Its low melting point allows it to be die-cast readily, with high production, low cost of operation, and remarkable precision of dimensions. In the early days there were two chief grades of zinc, one rather high in impurities but acceptable for galvanizing, the other a high-purity 99.95 percent product smelted from naturally pure ores. Even using this high-purity zinc as a material for alloys to be die-cast, the castings were not stable and were prone to crack in time. Such zinc die-castings had small commercial utility. In the search for methods of utilizing some complex ores containing zinc, electrolytic refining was tried and after painstaking research was made both successful and economical. When the solutions used were purified as the process itself demanded the product was zinc of 99.99 percent purity. Coincidentally with this development research had shown how to make and handle the die-casting alloys to insure stability and it had become clear that high purity was essential. Not only was the pure electrolytic metal at hand, but an electrothermic process was also developed which produced 99.99 percent zinc. From here the zinc-base die-casting industry progressed by leaps and bounds. Not only the decorative grilles on motorcars, which could be made from other materials, though not so cheaply for equal decorative appearance, but more vital parts such as fuel pumps for motorcars and many parts of other industrial machines are now zinc die-castings which serve adequately and cut costs materially.

Magnesium

A sizeable magnesium industry is being built up in the United States based on the use, as a raw material, of byproducts of the chemical utilization of natural brines and, in a plant now being constructed, on the utilization of sea water. These are very cheap sources of supply. Though it is occurring more slowly, the development of magnesium is following the pattern of that of the aluminum industry, in spite of the handicap of lack of corrosion resistance in some environments. Research has steadily improved the corrosion resistance and the mechanical properties of the magnesium alloys so that they are finding extended use. Due to special economic and political factors, the production and use of magnesium has advanced faster in Germany than in the United States, since some of the applications do not meet the same competition there from other materials of construction that they do here. Extension of our use of magnesium on a purely engineering basis is certain, because much research has already been done and the producers have a definite program for continued research that will inevitably result in still better materials. The price has already been progressively lowered so that the costs of magnesium and aluminum are practically equal on a volume basis.

Aluminum and Precipitation Hardening

About 30 years ago, Wilm, working in a Government research laboratory in Germany, discovered the heat-treatable strong aluminum alloy duralumin. Its heat treatment was on an empirical basis and its use did not develop rapidly, though some was used in Zeppelins during the World War. About 20 years ago, Merica and coworkers at the National Bureau of Standards discovered and clearly set forth the principles involved, putting the precipitation hardening by heat treatment on a rational basis. It was then possible to concoct other alloys that fitted in with the principles in the hope of securing analogous strengthening by analogous heat treatment, and to subject known alloys to suitable treatment in the hope of improving their properties. Today hundreds of useful alloys with a desirable combination of formerly unattainable properties are in commercial service. Beside a variety of aluminum alloys there are many copper-base alloys, including beryllium copper; steels, such as copper steels; lead-base alloys, nickel-base alloys, and special iron-tungsten and iron-molybdenum alloys the useful properties of which depend on the application of these principles. Improved methods of heat treating high-speed steels are based on them also. The principles likewise explain some harmful changes in low-carbon steels and in various alloys at high temperature and make it possible to avoid them to some degree.

Merica's work was one of the outstanding examples of the value of getting at fundamentals and of steering thinking into new channels. Getting our thinking out of ruts, often by borrowing ideas and methods from other fields, is not the least important byproduct of research. Another example of this may be cited.

Powder Metallurgy

Analogous to the practice common in the ceramic and plastics industries, of making products by agglomeration rather than by melting, the idea of pressing and sintering metal powder into coherent porous products, which may or may not then be worked into less porous form, has already been utilized in making ductile tungsten and the tungsten carbide tools. "Powder metallurgy" for the manufacture of porous, oil-retaining bearings, and as an alternative to forming by casting, or forging, or machining from solid stock, is on the horizon as a possibly important new branch of metallurgy, applicable also to the production of alloy combinations that cannot readily be made by older methods. In specific instances the method is well established; its widespread application is now more a matter of economics than of technology.

Adaptations From Other Sciences—Electron Diffraction

The application of the skills of other sciences to metallurgy is indispensable. Within the last decade the physicist has developed a new tool, electron diffraction, which showed promise of giving information about conditions at the surface of metals, the mechanism of the progress of corrosion, etc., that it was impossible to procure by previously existing methods. Metallurgical research workers soon took up the new tool and developed the necessary special technique, with great advantage to metallurgical science. Entirely invisible films only about a fifth of a millionth of an inch thick deposited upon the surface of metals have not only been shown by electron diffraction to be present there, but the composition and structure of the films have been established by the same means.[10]

Mineralogical Methods Utilized

The mineralogist has accumulated information on the composition and means of recognizing naturally occurring minerals, and together with the physical chemist, has developed methods of charting and recognizing what might be termed artificial minerals. He has used the petrographic microscope in his work, much as the metallurgist uses the metallurgical microscope. Those metallurgists engaged in the smelting of ores find it necessary to purify, or "beneficiate" the ores by mechanical separation of their wanted from their unwanted constituents. One method of separation is the flotation process previously mentioned in connection with molybdenum and copper. To make these separation processes applicable, the ore must be ground so that the particles of the desirable and the undesirable constituents are separated. If, however, the constituents are in such intimate mineralogical combination that separation by grinding is impossible, mechanical separation processes are inapplicable and chemical methods must be sought.

Application of mineralogical knowledge and technique allows the metallurgist to start at once upon the proper road of investigation. Mineralogical technique, including the use of polarized light, also serves the metallurgist in the study of nonmetallic impurities occurring as inclusions and thereby enables him to detect the source of the impurities and take steps toward eliminating them.

The physicist has developed the use of polarized light for studying stress distribution in transparent models. This is a matter of applied mechanics rather than metallurgy, but it greatly helps the metallurgist in that it proves that the designer can do much to mitigate stress concentration by proper attention to geometric form and is thereby enabled to reduce his demands for materials capable of resisting such high stress concentrations.

Instruments and Equipment

Modern metallurgical research requires equipment and instruments for precise quantitative measurements to an ever increasing degree. A great change in flying

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[10] Nelson, H. R. The low temperature oxidation of iron. *Journal of Chemical Physics, 6.* 606–11 (1938).

has taken place in the past decade; the airplane pilot no longer flies "by the seat of his pants," but with the aid of an imposing array of instruments. This change is paralleled in the research laboratory. The analogy is recognized in that the cockpit of today's plane is often termed a "flying laboratory." Research on new or more precise instruments and more dependable metallurgical tools is as necessary as is the research that uses them.

The Pyrometer

Although the metallurgist now assumes that precise measurement and control of temperature are axiomatic in any metallurgical process involving heating, this was not always so. The development of the thermocouple and of other means for measurement of temperatures was basic for all later developments in metallurgical science and technology.

The Induction Furnace

The development of the high-frequency induction furnace by Northrup, useful as it has proved to be commercially, was an especial boon to metallurgical research, for it increased the speed and precision with which melts of desired composition could be made. Incidentally Northrup was a professor when he began to work on his idea, but the commercial sponsorship and financial backing of the Ajax Electrothermic Corporation with its hope of private gain, were essential to the embodiment of the idea in tangible, useful form.

New Arms, New Conquests

As fast as we can free ourselves from the shackles of old modes of thinking and devise and utilize new instruments and more powerful tools, we can tackle problems that were hitherto unsolvable.

New facts and new principles remain to be unearthed and new applications of old ones remain to be made. The results should be as potent in serving human needs, developing industries and bringing employment, and wiping out dependence on strategic materials derived from abroad as those unearthed in the past have been.

Provision for the Future

If we admit this, and if we admit that metallurgy underlies all industry, we are ready to ask what provision is being made for continuation and expansion of metallurgical research.

Whence Will Come the Fundamental Metallurgical Research of the Future?

It is often stated that the universities are the fountain heads of "pure" or "fundamental" research from which flow the ideas on which the applied research of future generations will be based. This is hardly accurate in metallurgy. Even the initial, crude developments are likely to require expensive special equipment for the purchase of which university funds are seldom available. Smoothing out the crudities requires years of continuous effort, a time extending beyond that of a graduate course, so that the professor must work through a succession of students, each new one lacking the background of the previous ones.

With a commercial urge and the prospect of gain to be derived from utilizing information as soon as it is found, a well-financed industrial research group is far more likely to delve widely and deeply than a university can. With the incentive of commercial need, the research laboratories of the General Electric Company [11] sought ductile tungsten for the electric light more doggedly and at far greater expense than could have been the case in academic circles. A greater amount of theoretical work in metallurgy that might appear to be of highly abstruse nature, but which was required to forge a needed link in a commercial research chain, is encountered in the Bell Laboratories and the research laboratories of the Westinghouse and General Electric companies, than in the universities. Within the limitations of permissible cost of equipment, the Metals Research Laboratory of Carnegie Institute of Technology, Massachusetts Institute of Technology, and a few other schools, are working on fundamental metallurgical research problems with new information as much an objective as the training of men. Battelle Memorial Institute is doing the same sort of thing in several lines, notably in cast iron, on its own endowment. But, by and large, the bulk of the fundamental work is carried on at the direct expense of industry, as is the case with the work on rate of transformation of steel at moderate and low temperatures, at the Research Laboratory of the United States Steel Corporation.

Universities today are looked to more for the raw material from which research men are made than for a completely finished product, or for research results in themselves.

The Supply of Future Workers

Supplying such raw material is as essential as is the provision of instruments and equipment for research. One is of no more value without the other than is a plane without a pilot or a pilot without a plane. Unless the supply of research workers in metallurgy is maintained and augmented, a dearth of good men is imminent as soon as the metallurgical industries become as research-minded as the chemical industries are today.

Expert opinion [12] states that of all professions research is the most short-handed, there being a smaller reservoir of competent men compared to the need for them that

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[11] Hoyt, S. L. Ductile tungsten. *Metals and Alloys, 6*, 11 (1935).

[12] Job hunters. *Time*, p. 34 (December 25, 1939).

will exist when conditions improve. There certainly is no large reservoir of men already experienced in or being directly trained for metallurgical research, and the situation would be truly serious were it not for the still fairly adequate supply of raw material in the chemists, physicists, and engineers that are being turned out from the colleges.

Evaluation of what is needed in a metallurgical research man and of the various means that may be taken to produce such men, may therefore be considered as one of the primary topics in this discussion.

The Personality of a Research Man

To set the stage so that ever recurring dramas of metallurgical research can continue to be played in our national theater, we must have players who know how to develop the plot while speaking their lines, for there are no set lines and no prompt book in research—every scene calls for new dialogue. Not every man is a good actor, nor is every man, even with long technical training, a research man. The research man must have insatiable curiosity, pertinacity, and optimism, for he is hunting for something about the very existence of which he is uncertain and he must not be dismayed by early failures to find it. He must know the basic principles of the sciences concerned in his particular branch and must superimpose on this knowledge the detailed information called for in his particular project. Up to a certain point the basic training of the biochemist and the metallurgist might well be very similar, but the specific training of each would not greatly serve the other.

The Education of a Metallurgical Research Worker

In earlier days there was no formal scholastic training in metallurgy; the metallurgists were educated in the courses in engineering, chemistry, or physics and picked up their own metallurgy. It is still not very important that a research worker in metallurgy have a formal metallurgical training in his 4-year college course. He must be trained in modes of exact thinking, know a variable factor when he sees it, and know that he must hunt for it when he does not see it. There are able research metallurgists today who were self-educated beyond high school, though they are few. There are many who have had no metallurgical training at all in college but who were so well-grounded in the basic sciences that they were able to pick-up the needed metallurgical information very promptly by their own efforts. Indeed, many employers of research workers are not at all concerned about an applicant's ignorance of metallurgy if he has a sound foundation and the will to learn what he needs to but does not yet know. Formal courses in metallurgy and metallurgical engineering are not yet given in very many universities, and the courses that are usually given must prepare production men, sales engineers, and perhaps future teachers as well as research men. Hence, the curricula can hardly be expected to be aimed to turn out finished research metallurgists. This is no cause for worry. It will be cause for worry if too specialized metallurgical courses begin to crowd the fundamental courses out of the curriculum.

His Development

After a youngster has secured a sound background in the exact sciences, and either in college or by his own study has procured metallurgical information, he still has to develop that ability to tackle the unknown which differentiates the research from the production man or the sales engineer. This research ability to stand on his own feet may be gained by the right type of man either in graduate work or in a subordinate position in a research laboratory. A man cannot know, until he has tried it, whether he is the research type or not. The research laboratories of large metallurgical organizations often bring promising youngsters in from the production and control groups temporarily and send out with such groups for a time men who have served some apprenticeship in the research laboratory. This is done not only with the aim of giving each group an appreciation of the other's problems, but also with the idea that some of each will make the change permanent rather than temporary, thus fitting the square pegs into the square holes.

The process of natural selection and advancement from subordinate to more responsible research positions may not develop leaders rapidly enough. The necessity for doing routine research work may not give time for rounding out the man into one capable of constructive thought. The metallurgical industries are therefore showing interest in schemes by which a promising youngster, usually one with a year or more of graduate work in academic research, is given a fellowship in a research organization to work under close supervision of experienced research men on a problem chosen primarily to train the man in research methods and modes of thinking rather than for its immediate value to the sponsor. Alternatively, men in research organizations may be sent at company expense, or may go voluntarily at their own expense, to a university for graduate work. Either plan is generally far more fruitful than for the man to work directly on for a Ph. D. after procuring his first degree and without any interim spent on research or practice outside the academic cloisters.

There is, in normal times, no oversupply of men of proved capabilities for constructive metallurgical research. Long-range planning for the maintenance of a supply is worth while. High school boys should be given some inkling of the possibilities of metallurgy as a career so that they may consider it as one of the alternative occupations for which they might prepare while still undecided about what they want to do. Thus some might so choose their college courses, through not necessarily by taking metallurgy, that they would be sought by the metallurgical industries. This would aid in long-range planning for a steady supply of men for research.

Job Stability

It is likewise important to make sure that men fitted for ultimate success in research and with some accumulated experience are not unnecessarily diverted from research, or so placed that their past experience is not utilized. During valleys of the depressions of the past decade, especially the first one, some metallurgical research groups built up during the previous boom years, or somewhat replenished during periods of temporary improvement, were scattered overnight by executive decision, and many research metallurgists were thrown into the ranks of the unemployed. Those executive decisions in many cases have been repented and the research staffs again augmented, but, since the capable men usually found jobs with firms that did not disrupt their research groups, their experience was lost to their former employer. Security of tenure in research jobs seems greater now than at any time in the past.

Working Conditions

Consistent with the trend toward picking men with the right type of mind for research and who intend to make research their sole business, is the trend toward providing environment and working conditions that will favor efficient work. Many research laboratories are planned not merely for convenience, but attention is also paid to dignity of architecture. Numbers of such laboratories have been built in the last decade and stand as evidence of the importance of environment. In the direction of effective research, care is taken that the men have time to think. Extreme pressure for immediate results exerted on a research man seldom helps to produce those results. An atmosphere of much greater freedom than needs to be accorded the men of the routine control laboratory is called for.

Both for reasons of the workers' satisfaction and to promote efficiency in their work, there is a growing tendency towards complete relief of the research organization from the responsibilities of production control and trouble shooting. While every effort is made to have the research men in constant touch with the practical conditions of production so that they will keep their feet on the ground and be able to solve problems that arise, research is more and more being made a continuing, full-time activity rather than knitting work to be picked up and dropped according to the ebb and flow of plant difficulties.

Reasonable freedom for the research worker to publish his results and thus secure professional recognition is a factor in his satisfaction with his job, and generally benefits the employer as much as it does the employee. "Public relations" are benefited by publication.

The Written Word

No one thing affects the satisfaction and the efficiency of a research worker more than the availability of proper library facilities. The library is the most important tool of research. Moreover, if we are not to require prior formal metallurgical instruction of those engaging in metallurgical research, but intend to leave the door open to those of different basic training, upon which they themselves must superimpose a specific, self-acquired metallurgical education, the means for self-instruction must be at hand. The availability of printed metallurgical information, therefore, should be considered here. This situation is very satisfactory. The sharing of technical, scientific, and research information in metallurgy is carried on to high degree through the publications of the American Society for Metals, the American Institute of Mining and Metallurgical Engineers, The American Foundrymen's Association, the American Society for Testing Materials, the American Society of Mechanical Engineers, the Electrochemical Society, and others, together with technical and trade journals not connected with any society.

British society publications and journals, pretty much counterparts of the American ones, and a smaller number of useful metallurgical journals in Swedish, French, German, Italian, Japanese, and Russian, abstracted by United States and British abstract services, add to the bulk of printed information. The majority of the pages published on metallurgy contain reports on research. Indeed, though a metallurgical society starts out with the primary aim of service to the practical man and plans to make its meetings of the order of foreman conferences, in time it comes to placing emphasis on research in its publications. The early proceedings of the American Brass Foundrymen's Association, now the Institute of Metals Division of the A. I. M. E., compared with the often very abstruse theoretical publications of the Division today, show this. So do the early transactions of the American Society for Steel Treating, compared with those of its successor, the American Society for Metals. The same tendency is working in the American Electroplater's Society and the Wire Industries Association. The appreciation of research and the development of means for the dissemination of its results are characteristic of metallurgical societies.

Outstanding as a means of making new metallurgical information, obtained by research, available in authentic and condensed form, are the handbooks put out by the A. S. M., the A. F. A., the American Welding Society, and others. These are prepared by hundreds of experts who give their time free as a professional obligation. This allows wide distribution of the handbooks at very low cost.

Making readily available the research information of the world literature in its field is the task of the Alloys of Iron Research Committee which is in process of preparing monographs on the important iron-alloy systems. This useful, expensive, and still unfinished project was financed in part by Engineering Foundation, the National Bureau of Standards, and Battelle Memorial Institute, in large part directly by the metallurgical industries. There is nothing on foot in this country of a similar nature for the alloys of copper, but this gap is being filled by publications of the British Copper Development Association.

That one has to go outside the United States to find cooperative effort of just this type in the copper industry might be taken as evidence for the statement sometimes made that this industry is not so research-minded nor so cooperative as other metallurgical industries. The accusation is not justified as respects the producers of copper. That of something short of perfection in cooperativeness of the fabricators is more difficult to refute. That individual firms in the industry are doing highly useful research is known to those behind the scenes. The lack of appreciation of this among other scientists seems primarily due to the contrast in the publication policies of this industry with those of the steel industry. Such a case emphasizes the public-relations aspect of publications.

Textbooks and books of general metallurgical information written for reference use rather than for the classroom, and summaries of information, so-called "correlated abstracts," in restricted fields are appearing in greater numbers and of better quality. The technical societies hold symposia at which available information is reviewed to date and publish the papers presented. By these means the assimilation of metallurgical research is facilitated and home study is made more feasible than if the whole mass of literature had to be assembled and digested by each one who wanted to use it.

Assimilation through the spoken word is sought through the local chapter and regional meetings of such societies as the A. S. M. and A. F. A., which as a rule are planned to be more of an educational character than are the annual meetings of the various societies. However, a feature of some annual meetings is a special series of educational lectures, and some local technical groups conduct what might be termed adult-education evening schools in metallurgy. The the willingness of metallurgical industries to publish their research findings and to try to help the other fellow in the expectation of improving the whole industry is noteworthy.

Cooperative Effort

An outstanding example of lack of secrecy and active pooling of information is the open-hearth committee of the A. I. M. E., at whose meetings open-hearth steel furnace operators from all the steel companies get together to discuss experiences in increasing output, lowering costs, and increasing quality and uniformity. Great frankness is a feature of the meetings.

There is much joint research effort among different firms faced with the same metallurgical problems. Such activities are handled through committees of existing trade associations, of technical and scientific societies, or through temporary organizations set up for the particular occasion, which are not intended to continue after the present joint problems have been solved. Examples of these are the support by the American Electroplater's Society, the Non-Ferrous Ingot Producers' Association, and, of the temporary organization type, the Associated Silver Producers' work on development of industrial uses for silver. Cooperative work of industry with the Bureau of Mines is also carried on.

More widespread use of Government facilities is hampered by the patent policy of certain departments of the Government which allows Government employees to take out personal patents on work they do in the Government laboratories. Certain departments frown on this, but in the National Bureau of Standards, the Bureau of Mines, and the various research divisions of the Army and Navy an employee may elect to take out patents for himself, and if he does, the cooperator must make arrangements with the employee for the use of the patents. This situation often prevents industry from taking its problems to the Government laboratories when patentable features are likely to grow out of the work. In most university research foundations and the research institutes the patentable features are entirely the property of the sponsor. Patents are seldom as important in joint projects as they are in projects of an individual sponsor.

As a rule the Government laboratories are more eager to cooperate actively with a representative group on a joint problem than with a single firm, so on both sides the conduct of a joint investigation at a Government laboratory may have favorable consideration.

Modes of Joint Research

Committees of technical societies often meet research problems the solution of which would be to the joint advantage of a considerable portion of the industry they represent. This is particularly the case as respecting metallurgical problems with the American Society for Testing Materials and the American Society of Mechanical Engineers, both of which have research committees on various topics as well as committees for drafting specifications and codes. The American Welding Society has many metallurgical problems. In these, as well as in some other metallurgical societies, experimental research is carried on when the need warrants, usually as a committee or subcommittee project. The project may take the form of splitting the work into small sections each of which is carried out in the laboratories of the committee members, with subsequent pooling of results, the cash outlay being absorbed by the respective budgets of each cooperator. The work is subject to such delay as the exigencies of the other work of the laboratory may demand. This method is much used on small problems and often as an initial stage in larger ones.

When the effort required is beyond that which can be slipped in along with the other work of the cooperators, the committee collects funds from those who stand to benefit and who are willing to cooperate financially, and the work is hired done. Sometimes a research engineer is hired and facilities for his work secured at the National Bureau of Standards, a university, or an institute. Rarely is experimental work for the benefit of a group done for pay in the laboratory of one of the member companies, as this is seldom acceptable to the other cooperating firms, though the method has been used. More commonly the project is farmed out to a research foundation or research institute.

For example, work thus financed on various phases of problems of metals at high temperature has been simultaneously in progress at Massachusetts Institute of Technology, the engineering research division of the University of Michigan, and at Battelle Memorial Institute for the joint research committee of the A. S. T. M. and A. S. M. E. on Effect of Temperature on the Properties of Metals, while small projects on which work was donated by the laboratories of several manufacturers were also in hand.

Utilization of Outside Aid in Research

The successful conduct of a variety of joint research problems has made it increasingly evident that a firm does not necessarily have to carry on all its research under its own roof.

Business instability and fear of conditions beyond the control of business, indeed, make firms with manifold research problems and limited research staffs hesitant to build up large permanent staffs and to install elaborate equipment for their work and more prone to farm out specific problems to outside laboratories. Competently handling such farmed-out problems under adequate supervision and with adequate equipment is not easy for the average university professor who does, or should, make instruction his first duty. He lacks the time, and also his laboratory facilities for instruction are not adequate for research that must yield commercial results. Hence "engineering experiment stations" or special "research foundations" with full-time or nearly full-time professors to direct research, and with equipment suited to certain restricted lines of research, have sprung up in considerable profusion, besides the research institutes the sole purpose of which is to provide research facilities for industry. Several of these various types of organizations are specializing in metallurgical research, and these are kept increasingly busy.

Public Funds Not Available for Metallurgical Research

There is no mechanism by which the metallurgical industries can get their research done at public expense save to the extent to which they can secure cooperation or housing for research associates at Government laboratories such as those of the National Bureau of Standards or the Bureau of Mines. Through transfer funds to the former, the Navy and the National Advisory Committee for Aeronautics have had important metallurgical work done on their problems, the results of which have been valuable to industry. The Naval Research Laboratory has done useful work on steel castings. Though these researches have industrial value, that is a byproduct, the primary investigation having been made to secure information directly needed for purely governmental purposes. While these and other Government laboratories are not unmindful of research on fundamentals that affect the metallurgical industries, there is no Government research agency to serve metallurgy in any way comparable to that of the Federal Department of Agriculture and the State Agricultural Experiment Stations for agriculture. Nor is there any analogy to agricultural "extension" work. Through the Department of Science and Industry, England matches pound for pound up to a certain limit, the research funds provided by industry for such laboratories as those of the British Cast Iron Research Association, etc., in which public funds are devoted to metallurgical research topics selected by industry. The scheme is intended to encourage research by and for those who might not otherwise engage in it.

The endowed research organizations, as a group, do not do much in metallurgy. The projects of the National Research Council have in the past almost invariably been very far afield from anything metallurgical. The Engineering Foundation has provided funds to start work on several projects of metallurgical interest, including valuable pioneer work on fatigue of metals, and has contributed to specific projects of the A. S. T. M.-A. S. M. E. joint high-temperature committee, as well as to the alloys-of-iron research, which latter is, however, not of an experimental nature. Battelle Memorial Institute is an exception, since it does metallurgical research on its own funds and publishes the results. State and other university experiment stations do some valuable metallurgical research at State expense. But in all these cases the endowed or publicly supported institution selects the topic for research. In the United States, when a metallurgical firm or a group of firms wants a specific research problem investigated it foots the bill itself. From past results this does not appear to be a bad method for the future, so long as the incentive for private gain remains characteristic of the economy of our Republic.

Competition vs. Monopoly in Research

In spite of the fact that the prospect of private gain stimulates most of the worth-while metallurgical research, active competition within a given field does not necessarily make for the type of research that does the country the most good in the long run. Indeed, the opposite may be true.

Good research costs money. The subsequent development work and application to production usually costs much more money. This money is more readily obtained, and accounting more clearly shows a profit on investing it, when a strong firm, even a quasi-monopoly, is involved than when there are many producers of the same commodity. There is less delay in undertaking research that will bring out the possibilities and limitations of the commodity and thus make it possible for engineers to use it more intelligently. There is no domestic competition by primary producers of aluminum.[13] Primary and secondary aluminum compete, and aluminum competes with steel, copper, and other metals. Plastics offer potential competition to metals. There is no permanent gain in exerting sales effort to force a commodity into a service for which it is neither technically nor economically adapted. As Van Deventer of the Iron Age phrases it, each material has its own "supremacy areas" in which its technical superiority is so marked that it can readily overcome a cost handicap (silver in electrical contacts is a good example); other areas in which substitutes are plentiful and the choice is to be made on the basis of economics; and still others in which alternative materials are better both technologically and economically. As knowledge and experience grow these areas shift. Research to bring about a shift into supremacy area or to evaluate the shifts likely to occur through the research improvement of competing materials can be of immense value to the sales department.

The domestic producers of aluminum are outstanding in doing and reporting research that gives the cold facts about the properties so far built into aluminum alloys. When they report on fundamental facts, such as on the equilibrium diagrams for aluminum alloys, those reports are based on as precise work as any done in metallurgy and are accepted as quite as credible as if the work had been done by the National Bureau of Standards.

Very extensive research and development work by the producers of nickel has brought early and complete information on its usefulness as a metal and in alloys. If the nickel business were split up among a lot of producers, each much less able to finance research, the sum total of research information on nickel would probably be far less than we have today.

Conversely, silicon is produced by many firms, and in various forms, as ferro-silicon, silvery pig, etc. No one controls the "ores" of silicon. There are a number of alternate sources for many uses. While research on silicon is not wholly lacking, there is no comprehensive program for developing its potentialities comparable with those for aluminum or nickel. We lack understanding of the role of ladle additions of silicon to cast iron and use such additions empirically, probably inefficiently. Were there some firm to whom silicon were the "only child," one might reasonably expect that such a problem would not long remain unsolved by research.

That research is most easily inaugurated and financed by strong firms with a large volume of business that does not have to be divided among many competitors does not mean that research is not being done profitably by small metallurgical units in highly competitive situations. It is so done, as has been brought out by some of the case histories cited earlier.

Research in Relation to Employment

As Stevenson[14] points out, labor-*making* inventions leading to new industries require both longer-term research and more financial courage than the mere perfection of processes in minor details that lead to labor-*saving*. It takes courageous leadership to develop and exploit new and unusual projects. If 1 out of 10 off-the-trail research projects started by a research organization pans out worthy of commercial application, the organization is fortunate. The other 9 have to be paid for. Only when the management has the nerve to explore all 10 prospects thoroughly can it hope to mine the rich ore bodies that will repay the exploration costs for all. Not only must the man-

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[13] Since this was written, a second producer is arranging to enter the field.

[14] Stevenson, A. R. Requisites for engineering leadership. *Mechanical Engineering, 61,* 903–6 (December 1939).

agement have the vision and the financial resources to ask for and pay for the development of new things, but it must have research talent available that is competent to undertake the development with a reasonable chance of success. There are a score of men who can lick a plant production problem and work out a way of doing a job more efficiently to one who can blaze a trail to a new industry that will employ many more men.

There are blind spots in metallurgical research like the one just mentioned concerning silicon, and for another example, the broad problem of finding what properties are really needed in a bearing metal, and how to measure them. These need extensive research. Sufficiently comprehensive work has not been set in motion upon them, nor is there readily available the mechanism for bringing together those who need light on some of the many facets of the problem and arranging for the long-term financing that would be required. There are committees who could make such a task of starting things their business, but these projects do not start themselves.

Research on Research

One of the most baffling problems met by the metallurgical consultant is presented when a firm or a trade association of an industry says, "We are sold on the general idea that research is necessary for progress, but we have not been able to settle upon specific research problems whose solution would advance our position, much less are we able to determine the one or two problems that deserve first attack. What shall we do?"

Here research to determine the future course of other research is called for. The best way to find the spots to which we have hitherto been blind, is to illuminate the background. If the suitability of the firm's plant, equipment, and personnel is evaluated, some special strength or weakness may be uncovered that makes it obvious that work on a specific product or on strengthening some weak link in the process, is in order.

In the case of a whole industry, if an evaluation is made of the "supremacy areas," including the nature of present and potential competition, with a clear statement of the scientific fundamentals on which the technology and economics of the industry are based, these facts, put down in black and white, generally clarify the situation. Such an evaluation usually brings to light problems whose immediate importance is recognized by all, once they are clearly stated. Then research may be applied to these problems.

True vs. Alleged Research

There are "research departments" in metallurgy, as in other industries, that give lip service to research and are really nothing more than control laboratories under a more imposing name, so called for the advertising value of that name. These cases are less common than formerly and it often happens that because the name is used more thought is given to the possibilities of real research and it is finally undertaken. However, statistics purporting to show the funds and the manpower applied to research are likely to include both the alleged and the real, and are therefore of doubtful value.

Acceptance of Research

On the whole research has proved its utility to the metallurgical industries, and is accepted by them as one of the essential steps in maintaining present markets, finding new markets, creating employment, and cutting over-all production costs so that in spite of mounting labor cost and taxes, their products may still go to the customer at steadily decreasing prices and with wider distribution.

It is this final effect upon the consumer that classes metallurgical research among national resources, to be conserved and fostered.

Summary

To sum up, metallurgical research is demanded in order to promote progress in the production and use of metals, not only in instances where the final products are metallic, but equally where the metals are incidental.

Metallurgical research is provided by the laboratories of the producers of metallic raw and semifinished materials. Such laboratories have to deal with a mixture of process improvement, product control, service to customers which may involve some research, searching for new applications to broaden the market, maintenance of the competitive position against substitute materials, and such delving into fundamentals as these problems require.

Metallurgical research is provided by the research laboratories of industries which use metals and have specific problems to which improved metals are the answer. These laboratories have no predilection for one metal over another; they run the whole gamut. Their attack may thus often be broader than that of those who have a specific axe to grind.

Metallurgical research is provided by joint research on specific problems where producer and user cooperate, exemplified by A. S. T. M. committee projects.

Metallurgical research is provided by specialized institutes, which serve to extend the facilities of all the groups above mentioned, as well as to do fundamental metallurgical research on their own initiative.

Metallurgical research is provided, on a smaller and usually a more localized basis, by university experiment stations and by the part-time consulting service of individual professors.

Metallurgical research is provided by Government research laboratories, which are increasingly engaged upon problems relating to national defense, but pay attention also to problems confronting the metallurgical industries.

Finally, metallurgical research is provided as a by-product of the training of research workers by the universities, their major and essential contribution being the initial training of the individuals who will ultimately bear the burden of the metallurgical research of the future.

Moreover, the results of metallurgical research are made public and shared in a cooperative spirit, even though individual profit is necessarily the ruling motive.

All these kinds of metallurgical research are essential. None is so fully developed as it will be, but even in their present status, they all together form no inconsiderable item in an accounting of national economic resources.

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SECTION VI

6. THE CHEMICAL ENGINEER IN INDUSTRIAL RESEARCH

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ABSTRACT

Although comparatively a newcomer among the scientific and engineering professions, the chemical engineer has rapidly assumed an important responsibility in industry. His work has been largely concerned with the development and application of those manufacturing processes that involve chemical and certain physical changes in materials. Thus he finds his principal opportunity in the chemical and so-called "process" industries.

Chemical engineering research per se is largely confined to the improvement of processes through the quantitative study of the fundamental theory underlying the unit physical operations, such as distillation, evaporation, absorption, filtration, mixing, and agitation, and the unit chemical processes, such as oxidation and reduction, chlorination, nitration, and sulphonation. A much broader field of activity lies in "development" work as contrasted with the research of the laboratory. Here the chemical engineer supplements the creative work of the research scientist by translating his laboratory studies into larger-scale operations. This translation is often effected in the semiworks or pilot plant which has thus come to be known as the true habitat of the chemical engineer. It is here that he studies a new process under plant conditions, designs and constructs the equipment for commercial production.

By training and experience the chemical engineer is often well qualified to determine the economic feasibility of many research projects. An increasing number of chemical engineers are therefore employed in commercial and market studies that help to give direction and effectiveness to programs of technological research. Much of the success of chemical industry in the development of new products and processes has resulted from the fact that its research has been conducted on an engineering basis from the first selection of the project to the final utilization of the product in the plant of the customer.

Despite recent progress in chemical engineering research, many features of equipment design and operation remain on an empirical basis. They await fundamental study. There is likewise abundant opportunity to extend the application of fundamental data and principles to many industries that have not yet been benefited by this relatively new technology. In the words of a great mining engineer, "Chemical engineering, more than any other, may be called the engineering of the future."

Research is an important function but scarcely the primary activity of the chemical engineer in industry. His contribution supplements and helps to make effective the work of the research scientist by translating the findings of the laboratory into terms of large-scale plant operations. This is more accurately described as process development work and in many industrial organizations, research and development are closely linked activities. They are usually administered in the same department and it is sometimes difficult to say where the one begins and the other leaves off.

The relation of development work to the other duties of the chemical engineer is evident from the following definition of chemical engineering, which was suggested by the writer in 1935 and has since been adopted by the American Institute of Chemical Engineers' Committee on Chemical Engineering Education.[1]

> Chemical engineering is that branch of engineering concerned with the *development* and application of manufacturing processes in which chemical and certain physical changes of materials are involved. These processes usually may be resolved into a coordinated series of unit physical operations and unit chemical processes. The work of the chemical engineer is concerned primarily with the design, construction, and operation of equipment and plants in which these unit operations and processes are applied. Chemistry, physics, and mathematics are the underlying sciences of chemical engineering and economics its guide in practice.

Chemical engineering, as we know it today, is a com-

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[1] Newman, A. B. Development of chemical engineering education in the United States. *American Institute of Chemical Engineers, Supplement to Transactions*, 34, No. 3a, 7 (1938).

paratively new profession. It may be said to have had its origin in the unit-operation concept first presented by the late Dr. Arthur D. Little in December 1915, in a report to the Corporation of the Massachusetts Institute of Technology, which ultimately led to the foundation of the School of Chemical Engineering Practice at that institution. Dr. Little then defined chemical engineering in these terms:[2]

> Any chemical process, on whatever scale conducted, may be resolved into a coordinated series of what may be termed "unit actions" as pulverizing, mixing, heating, roasting, absorbing, condensing, lixivating, precipitating, crystallizing, filtering, dissolving, electrolyzing and so on. The number of these basic unit operations is not very large and relatively few of them are involved in any particular process . . .

As this concept of chemical engineering gradually displaced the older methods of teaching industrial chemistry in our educational institutions, its practitioners in industry began to apply quantitative study to the fundamental principles and theories underlying these unit operations and processes. Thus developed what is truly chemical engineering research as distinguished from purely chemical research. Dr. Little[3] well stated its objectives in the following words:

> Chemical engineering research . . . is directed toward the improvement, control and better coordination of these unit operations and the selection or development of the equipment in which they are carried out. It is obviously concerned with the testing and the provision of materials of construction which shall function safely, resist corrosion, and withstand the indicated conditions of temperature and pressure. Its ultimate objective is so to provide and organize the means for conducting a chemical process that the plant shall operate safely, efficiently, and profitably.

Fields of Application

The introduction of the dollar sign into the chemical equation proved a potent stimulant for industrial research. As new products and processes began to emerge from the laboratories in ever increasing number, more and more companies came to realize that their future dividends depended upon scientific development. During the 1920's, therefore, there was a steady growth in research activities and a corresponding increase in the requirements for technically trained personnel. The number of chemical engineers entering research and development work followed the general trend, but it is interesting to note that in some industries there was much greater demand than in others. In other words, there was a relatively deeper penetration or acceptance of chemical engineering in those industries that could make most effective use of men with this training.

Among the first to utilize the services of the chemical engineer were the more strictly chemical industries—i. e., the producers of heavy, inorganic chemicals, electrochemical products, coal-tar dyes and synthetic organic chemicals, explosives, artificial resins, fibers, and plastics. The basic chemistry of most of these processes was relatively well known, but there was urgent need for better engineering in its application. Even by 1925 it had been estimated that the chemical-engineering penetration in this field was practically complete as regards the acceptance of chemical engineers in development work and the supervision of plant operation. Today these strictly chemical industries employ approximately 4,000 chemical engineers, of whom 750 to 1,000 are engaged in research and development work.

Somewhat slower to accept chemical engineering in the beginning, but now among its most ardent supporters, are certain of the so-called process industries such as petroleum refining, coal processing, and pulp and paper manufacture. These industries all depend upon such fundamental unit operations as heat transfer, distillation, evaporation, and fluid flow, for which there was abundant opportunity to apply improved processes and equipment, with resultant savings in capital and operating costs. It is not surprising, therefore, to find that even ten years ago the petroleum-refining industry was the largest single employer of chemical engineers, accounting for 12.30 percent of the graduates of the classes of 1920–29, according to a survey made by the American Institute of Chemical Engineers.[4]

Pulp and paper and coal processing at that time employed only 4 and 4.30 percent respectively of the chemical engineering graduates of the 1920–29 classes. But it should be remarked that the great recent growth of the paper industry, particularly in the Southern States, is rapidly changing this relationship. So, too, is the allied development of cellulose products for resins, lacquers, and rayon. Perhaps there should also be included in this second group the manufacturers of rubber goods, fertilizers, sugar, and certain food products in which it has been estimated that there has been a chemical-engineering penetration of at least 50 percent.[5]

This leaves still a third classification of industries in which chemical engineering has made relatively slower progress—with 50 percent or less penetration. Among these are leather and textile processing, which are typical of those industries that are highly developed as arts but not as chemical-engineering operations. To a lesser degree the same situation applies in the manu-

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[2] Little, Arthur D. Twenty-five years of chemical engineering progress; silver anniversary volume. (American Institute of Chemical Engineers.) New York, D. Van Nostrand Co., Inc., 1933, p. 7.

[3] Twenty-five years of chemical engineering progress, pp. 7-8. See footnote 2.

[4] White, Alfred H. Occupations and earnings of chemical engineering graduates. *American Institute of Chemical Engineers, Transactions*, 27, 221–50 (1931).

[5] Industry's common bond in chemical engineering. *Chemical and Metallurgical Engineering*, 35, 5 (January 1928).

facture of ceramics and of glass, soaps, fats and oils, and perhaps even in that of paint and varnish, although the introduction of synthetic resins and newer pigments has recently stimulated great interest in new technology in this field. None of the last-named industries accounted for more than 1 percent of the 1920–29 graduates according to the American Institute of Chemical Engineers' study. By the same token, however, it is in these industries that most remains to be done and wherein there are the most attractive opportunities for capitalizing on scientific research and chemical-engineering development.

Adequate statistics are lacking for the total number of chemical engineers engaged in research and in development work. The survey made by Professor White for the American Institute of Chemical Engineers in 1931 would seem to indicate that for the men receiving bachelor's degrees in the classes of 1920–29 approximately 25 percent were engaged in research and semiplant development. An even larger proportion of those with graduate training are so employed.

Dr. Harry A. Curtis, has estimated that fully 30 percent of all chemical-engineering graduates go into semiworks development of one kind or another.[6]

In the study made by George Perazich for the national research project of the Work Projects Administration[7] it was shown that of approximately 20,000 research employees, 5,635, or 28.5 percent, were chemists and 4,594, or 23.2 percent, were engineers. Applying these percentages to all industries, Perazich estimated that the total number of engineers might be 10,000, but no attempt was made to classify them as chemical, electrical, and mechanical engineers.

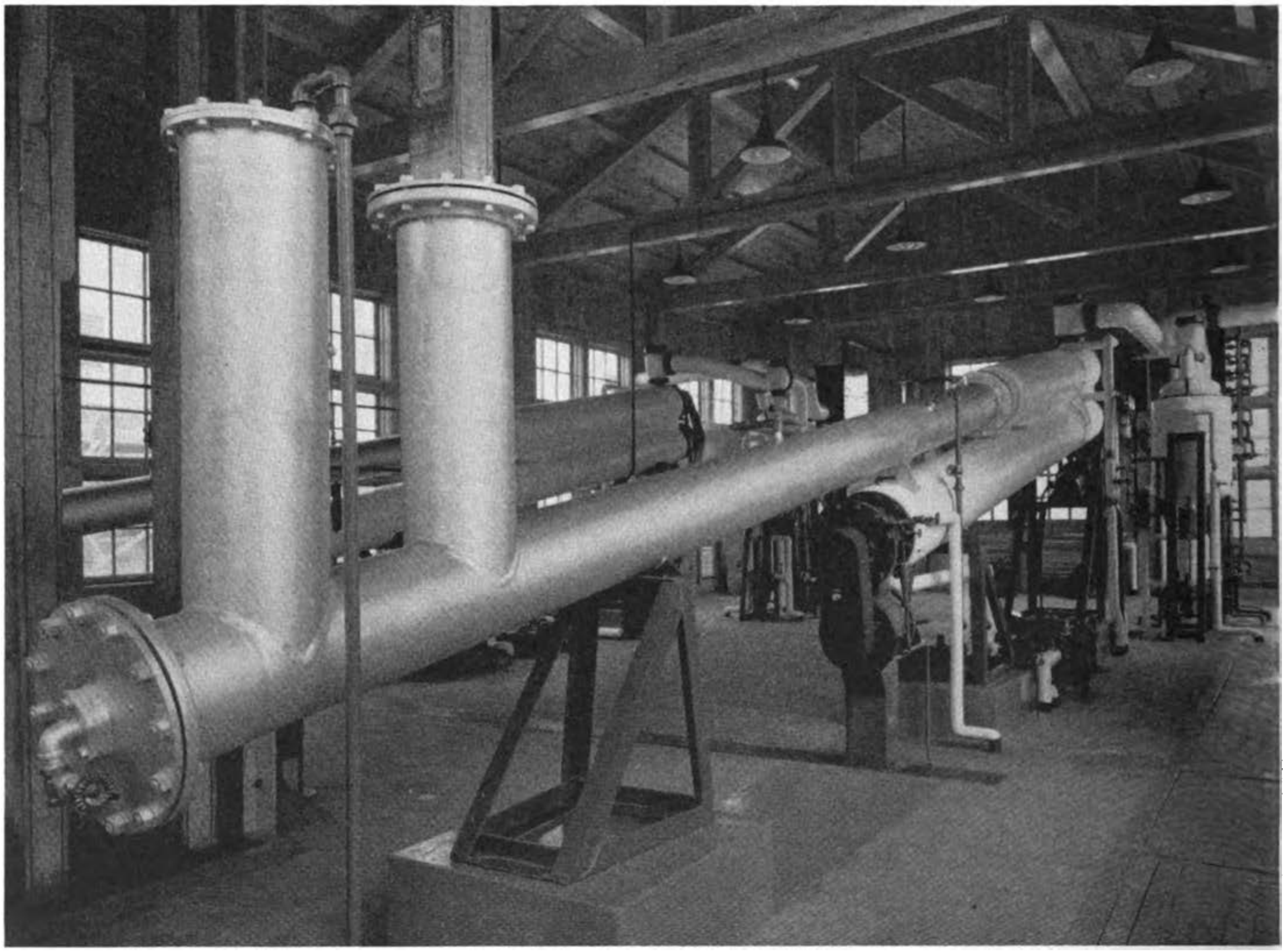

FIGURE 91.—Pilot Plant for Study of Soybean Oil Extraction, Ford Motor Company, Saline, Michigan

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[6] Curtis, H. A. Discussion of Pierce, David E. The half-way house. *American Institute of Chemical Engineers, Transactions*, 29, 100–11 (1933).

[7] Perazich, George. Growth of research in the United States, 1920–38. Philadelphia, Pa., Work Projects Administration, national research project, 1940, p. 321.

Functions in Research and Development

Until about 20 years ago, chemists and chemical engineers were used almost interchangeably in research and development work. At that time it was common practice to start all new men in the analytical laboratories and subsequently to transfer into research those who developed originality and creative abilities. Some of those unfitted for investigational work went into production or sales, while a few remained in the laboratory as routine analysts. Thus personal characteristics and aptitude rather than training and experience were the usual bases of selection. Sometimes the process worked admirably, but often it resulted in vocational misfits.

Universities perhaps contributed to this unfortunate situation somewhat by encouraging chemical-engineering graduates to go into laboratory research even though they were inadequately trained for this important work. Likewise, many research chemists were urged unwisely to enter pilot-plant and development work for which they lacked the engineering knowledge and training.

Gradually, however, this situation has been corrected. There has arisen a fairly definite division of functions and responsibility between chemists and engineers in research and development work. W. L. Badger, former professor of chemical engineering at the University of Michigan and now manager of the consulting engineering division of the Dow Chemical Company, has outlined this division as follows:[8]

> 1. The strictly laboratory work (i. e., the beaker and test-tube-scale operations) should be done by the man with chemical background and training. Engineering considerations do not ordinarily enter into the actual conduct of research at this stage.
> 2. The pilot plant, semiworks, or similar development should be in the hands of the chemical engineer, not only with regard to the work itself but also with regard to its direction. Through this stage, however, the chemist, although not taking the responsibility, should be closely associated with the engineer.
> 3. The design of the final plant and its operation are the work of the chemical engineer alone. Once the process has passed the pilot-plant stage, the function of the chemist is largely to control quality and to advise in case of chemical difficulties.

An important advantage of this form of organization is that the close association of the chemist and the chemical engineer prior to and during pilot-plant operations makes possible an exchange of knowledge and experience that could not be obtained through reports or infrequent conferences. This exchange of experience, and the enthusiasm and inspiration that

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[8] Private communication.

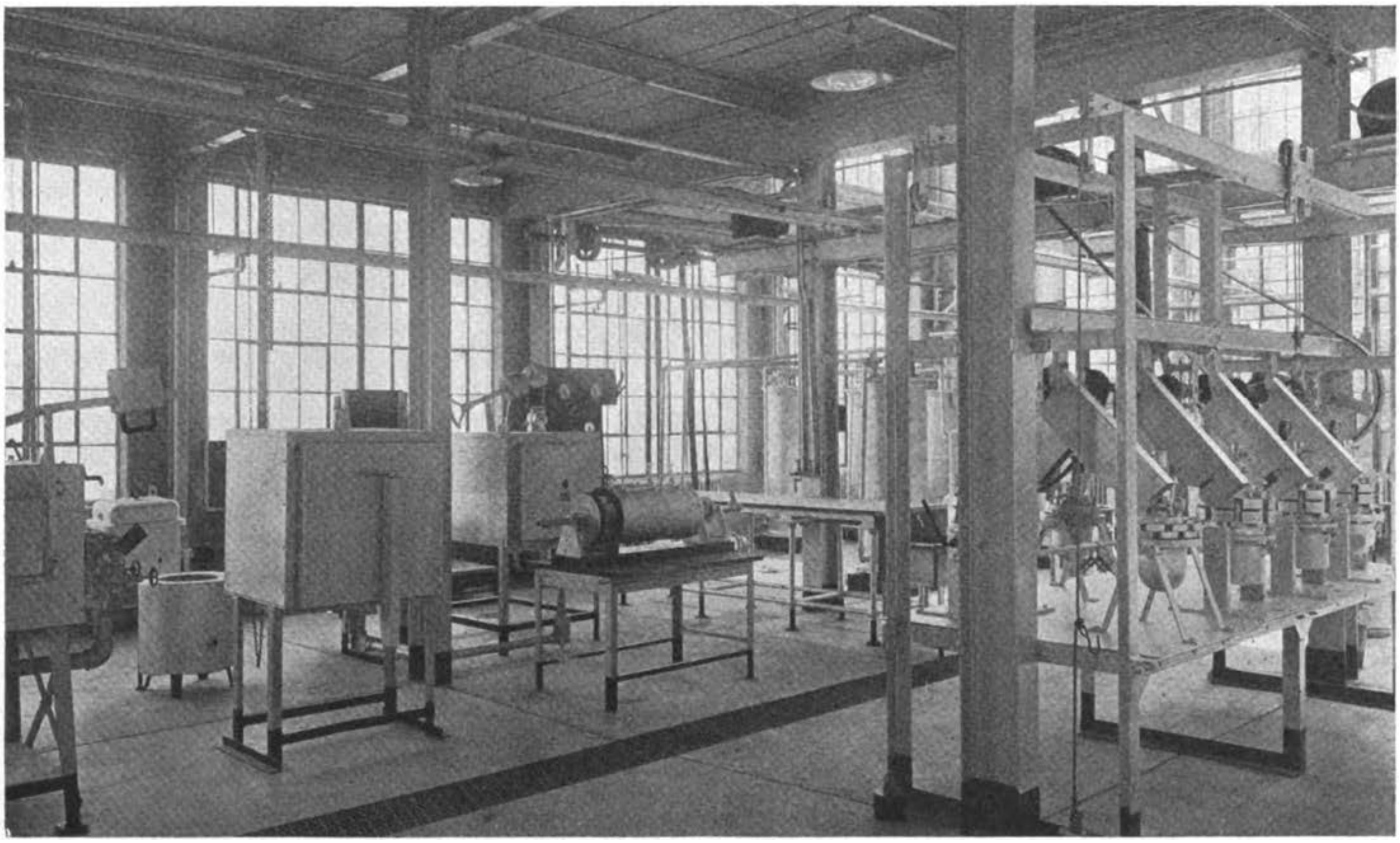

FIGURE 92.—Chemical Engineering Laboratory, Aluminum Research Laboratories, Aluminum Company of America, New Kensington, Pennsylvania

accompany it, form an essential part of successful development work.

Dr. M. C. Whitaker, vice president of the American Cyanamid Company, calls attention to the direct contribution the chemical engineer can often make by advising research men as to the feasibility of proposed operations as well as by helping them to design special types of laboratory equipment required for this work. In a private communication, he writes as follows:

> Chemical engineers fit into our research and development program from the time the job leaves the research laboratory until the customer has bought our goods and actually used them up in his own operations. In other words, chemical engineers take the laboratory processes, and with the assistance of the research chemists they design, develop, and operate pilot plants for experimental production. Then, on the basis of this experience, they design and install the full-scale production equipment, direct the operation of the plants, collaborate with the sales department in the introduction of the new materials, and, finally, instruct the customer in his application and use of the end products of our research.

This liaison function of the chemical engineers is becoming more and more important in modern industry. This is especially true in the larger companies where the transition from the laboratory to the pilot plant and from semiworks to full-scale production is often between different departments or widely separated plants. In a small plant, however, which can employ only one or two chemical engineers, there is not likely to be any such well-defined division of duties. Here the chemical engineer must not only do the pilot-plant work but may be responsible for designing, building, and even operating the commercial plant.

In general, however, most companies try to divorce research from plant operation not only because the latter is a full-time job but also because it generally calls for quite different qualifications. Nevertheless, some very successful companies make it a practice to start their young chemical engineers at the bottom of a development group and, after they have advanced to the point where they can undertake it, to assign them to a problem through the design, construction, and operating steps, and finally make them operating heads of the process.

The American Potash and Chemical Corporation follows a modification of this procedure. Its research director, Mr. W. A. Gale writes:

> On new developments we usually assign the investigation to some one man who will be expected to carry the problem, if all goes well, through all the various stages of preliminary development. The detailed design and construction of the commercial plant is handled by the engineering department, but the research and development department must develop the preliminary design and specifications, such as volumes of material to be handled, quantities of heat to be transferred, and general type of equipment and flow sheet arrangement, and must prepare preliminary estimates of operating costs. Then when the plant is finally built, the research man will know more about it than almost anyone else, so he will be given a large part in supervising the testing, training of the crew, and preliminary operations until such time as the plant is turned over to the production department as a smoothly operating unit. For this work we find that a man with good chemical-engineering training is much more useful to us than a man who has been trained just as a chemist or physicist.

The Pilot Plant

The true habitat of the chemical engineer is in what David E. Pierce,[9] of Charles Lennig and Company, has called the "halfway house of industry"—the semiworks or pilot plant in which is determined the success or failure of most new processes. Here, halfway between the test-tube research and full-scale operations, the chemical engineer finds his greatest opportunity. It is his function to study a new process, to check its behavior under plant conditions, and to perfect the design and construction of the equipment before the project is ready for commercial production. Dr. L. H. Baekeland is usually credited with the advice "Make your mistakes on the small scale and your profits on the large."

Pierce has summarized the four functions of the semiworks plant as follows:

1. To study new processes or new types of equipment in order to secure data for plant design;
2. To study proposed variations in old processes in order to increase yield or quality, or to improve the design of equipment;
3. To make sample batches of new products for introduction to the trade; and
4. To manufacture for sale new or special products for which the demand is not yet large enough to justify full-scale plant operations.

University and Institutional Research

Not all chemical engineers in research and development work are directly employed in industry. Many are in the universities where an increasing volume of both fundamental and applied research work is being done. As will be noted later, the chemical engineer's direct contribution to fundamental research is largely confined to studies of the physical and chemical factors affecting the unit operations and processes. Such investigations are concerned with advances in theory and knowledge of the underlying principles. Only recently has there developed any appreciable need in university research organizations for chemical engineers who are proficient in pilot-plant design and operation.

This situation does not necessarily obtain in some of the public and privately endowed research institutions. Governmental departments, as exemplified in the set-up of the four new regional laboratories of the United

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[9] Pierce, David E. The half-way house. *American Institute of Chemical Engineers, Transactions*, *29*, 100-111 (1933).

States Department of Agriculture, under the Bureau of Agricultural Chemistry and Engineering, definitely provide for chemical-engineering divisions to have charge of the semicommercial development and the small-scale manufacture of products resulting from research. The Mellon Institute of Industrial Research, in Pittsburgh, and the Battelle Memorial Institute, at Columbus, Ohio, are both large employers of chemical engineers. Mr. Clyde E. Williams, director of Battelle, states that approximately 15 percent of their entire technical staff have had chemical-engineering training. Although a number serve as operators of chemical pilot-plant equipment, many are also serving as supervisors, research engineers, and assistants in such fields as electrochemistry, ceramics, fuels, nonferrous metallurgy, powder metallurgy, and many other phases of iron and steel research. Mr. Williams writes:

> We choose and advance men largely on their qualifications and abilities to do good research work. In other words, the primary requirements are broad training in fundamentals, ability to apply results, and to think in a practical manner; imagination, inquisitiveness, and ability either to direct or to conduct research investigations. Chemical engineers are chosen for certain problems because of their specialized training or experience, but on the whole their ability to master and apply fundamentals is more important than the type of training.

These research institutes work closely with the research and development departments of the industrial companies that sponsor their projects. Often a comparable function is served by a firm of consulting chemical engineers. Several of the larger organizations in this field maintain extensive laboratory facilities and pilot plants, well staffed with competent personnel for carrying on research and plant development work. There are many more research consultants, however, who merely serve as advisers to industry—contributing the advantage of an outside viewpoint and the value of diversified experience, both of which are helpful in the solution of research problems and the direction of industrial development.

Technological Research

The earliest practitioners of chemical engineering relied largely on the accumulated experience of those who, by methods of trial and error, had slowly developed the first crude chemical manufacturing processes. Empirical considerations still control many features of equipment design, construction, and operation in chemical industries. There is still some truth in the old saw that the engineer is a man who must draw sufficient conclusions from insufficient data. Nevertheless, fundamental research is gradually changing what was once an art into something that today approaches a more or less exact science.

Dr. Charles M. A. Stine, of the du Pont Company, noted the significance of this trend a dozen years ago when he remarked:[10]

> Perhaps the characteristics which most clearly differentiate the chemical engineering of today from the earlier activities of those interested in this field is the *quantitative* treatment of the various unit operations, and it is this exact and quantitative treatment of these operations which constitutes the province of modern chemical engineering.

Further evidence from the same source may be noted in the publications on chemical engineering which have come from the experimental station of E. I. du Pont de Nemours & Company, Inc., in the period 1930–40. A comprehensive list compiled for the writer by Thomas H. Chilton shows 42 papers dealing (quantitatively in most cases) with the following unit operations: Fluid flow (11 papers), heat transfer (7 papers), distillation, boiling and condensation (9 papers), absorption (4 papers), drying (2 papers), mechanical separation (1 paper). Five other papers dealt with corrosion and materials of construction while 2 were concerned with broader reviews of research problems.

In his Chandler Medal lecture at Columbia University on November 16, 1939,[11] Chilton gave an account of an extended series of chemical engineering researches attempted to formulate quantitative expressions for predicting the rate of transfer of materials to fluids in motion. Knowledge of these rates is essential in order to predict the size and performance of equipment used for absorption, condensation, distillation, extraction, and humidification—important unit operations in most of the process industries. Research of this sort not only simplifies the problems of chemical engineering design, but is of great practical value that can be measured in increased yield, improved quality, and worthwhile economies in fuel and power consumption.

The petroleum industry has likewise been a productive source of fundamental chemical engineering research on distillation, heat transfer, and the diffusional processes. Publications from industrial laboratories of the Standard Oil Development Company, the Standard Oil Company of Indiana, the Atlantic Refining Company, the Universal Oil Products Company, the Cities Service Company, the Gulf Oil Company, and the Shell Development Company, have been especially noteworthy. The public utilities, as represented by the Utilities Research Commission at the University of Illinois and the United Gas Improvement Company of Philadelphia have sponsored invaluable research on the important unit operations and processes involved in fuel production and utilization. All this has been reflected in more efficient equipment and processes for these industries.

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[10] Stine, C. M. A. Chemical engineering in modern industry. *American Institute of Chemical Engineers, Transactions, 21*, 46 (1928).

[11] Chilton, Thomas H. Engineering in the service of chemistry. *Industrial and Engineering Chemistry, 32*, 23–31 (January 1940).

Manufacturers as well as users of chemical engineering equipment have participated in this advance. The experimental station established a number of years ago by the Swenson Evaporator Company at the University of Michigan and under the direction of Prof. W. L. Badger and coworkers [12] has contributed valuable knowledge and experience that have been the basis of improved design. Work done at the Western Precipitation Company's laboratories in Los Angeles on electrostatic precipitation [13] is typical of fundamental investigations carried on by an equipment manufacturer. Extensive facilities for this type of investigational work are maintained by the Dorr Company at Westport, Conn., by the Lummus Company in Elizabeth, N. J., the M. W. Kellogg Company in Jersey City, E. B. Badger & Sons Company in Boston—to name only a few laboratories that have been described in current literature.

Apart from quantitative research on the unit operations and the design and performance studies of the equipment manufacturers, there is a broad field of chemical engineering activity concerned with the development of entirely new manufacturing processes. Here all of the chemical engineer's knowledge and resourcefulness are called into use. Most important of his responsibilities are the lay-out of the process flow sheet based on material balances, heat, and power followed by the design or the selection of the necessary equipment of the proper materials of construction, through the testing and experimental operation of the pilot plant and, finally, to the transition to full-scale production.

One can read an absorbing account of 15 years spent in such a development by Dr. A. M. McAfee [14] of the Gulf Refining Company. In 1915 he read a paper before the American Institute of Chemical Engineers proposing the use of anhydrous aluminum chloride in refining petroleum. This material was then only a laboratory reagent, selling for $1.50 a pound. But if his refining process was to succeed, he needed tons of it and it had to be cheap. Therefore he and his associates at Port

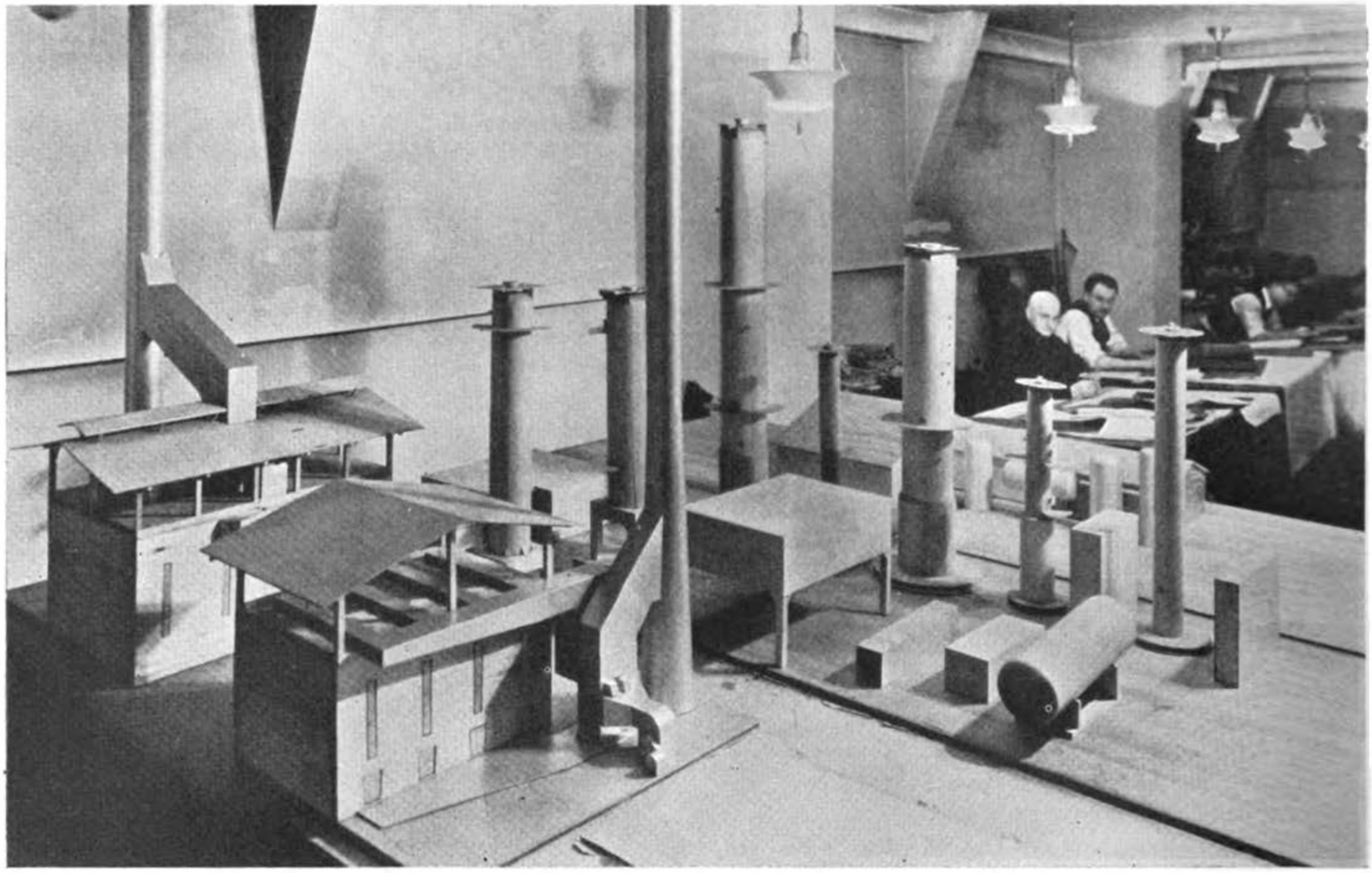

FIGURE 93.—Modern Dubbscracking Plant, Modeled in Wood, Equiflux Heater at Left, Universal Oil Products Company, Chicago Illinois

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[12] Hebbard, G. M., and Badger, W. L. Steam-film heat transfer coefficients for vertical tubes. *Industrial and Engineering Chemistry, 26*, 420–24 (April 1934); Logan. L. A., Fragen, N., and Badger, W. L. Liquid film heat—transfer coefficients in a vertical-tube forced circulation evaporator. 1044–47 (October 1934).

[13] Lissman, Marcel A. An analysis of mechanical methods of dust collection. *Chemical and Metallurgical Engineering, 37*, 630–34 (October 1930).

[14] McAfee, A. M. The manufacture of commercial anhydrous aluminum chloride *American Institute of Chemical Engineers, Transaction, 22*, 209 ff. (1929).

Arthur, Tex., started a series of experiments that extended over a period of 15 years and naturally involved many disappointments. However, in 1929 he was able to report, again to the American Institute of Chemical Engineers, that a successful process had been developed by which aluminum chloride could be made from crude bauxite ore and chlorine at the rate of 75,000 pounds per day and at a cost which permitted its sale in carload lots at 5 cents per pound.

Many equally interesting stories of chemical engineering developments might be cited except for the fact that they have seldom been told in their entirety. One notable exception [15] is the Victor Chemical Company's development of the fuel-fired blast furnace for phosphoric acid. Another is in the case of the work on phosphatic fertilizers done at Muscle Shoals by the Chemical Engineering Division of the Tennessee Valley Authority under the direction of its former chief chemical engineer, Dean Harry A. Curtis of the University of Missouri.[16] In this comprehensive series of articles are cited all of the many difficulties that arise to block the path of the chemical engineer in a typical large-scale development of new manufacturing processes.

In 1933 *Chemical and Metallurgical Engineering* announced a biennial award for chemical engineering achievement to recognize those companies that had made outstanding contributions to the industry and profession as a result of broader participation on the part of chemical engineers. The first company to win this award was the Carbide and Carbon Chemicals Corporation for its pioneering work in building a synthetic organic chemical industry in this country based on the hydrocarbons of petroleum and natural gas. This was a typical American development, resulting from original research conducted in the laboratories of Mellon Institute by American chemists and then translated into commercial development by American chemical engineers, first in a pilot plant at Clendenin, W. Va., and later in a tremendous industry at South Charleston, W. Va. The second award for chemical engineering achievement, in 1935, went to the organic chemicals department of E. I. du Pont de Nemours & Company, for the development from acetylene of the synthetic rubber known as neoprene and the synthesis of camphor from American turpentine. Here the academic researches of the late Father J. A. Nieuwland, supplemented by the work of du Pont organic chemists, were made productive through chemical engineering development work of a high order. The next award, in 1937, was to Monsanto Chemical Company which in that year had completed a program of chemical engineering research and development and had built a large electric furnace plant in Tennessee for the production of elemental phosphorus in tank-car quantities. This opened a whole new field for phosphorus as a heavy chemical in industry.

The most recent award in this series was made in December 1939 to the Standard Oil Development Company, which has long been a leader in developing and applying chemical engineering processes in petroleum refining. It had introduced high-pressure hydro-

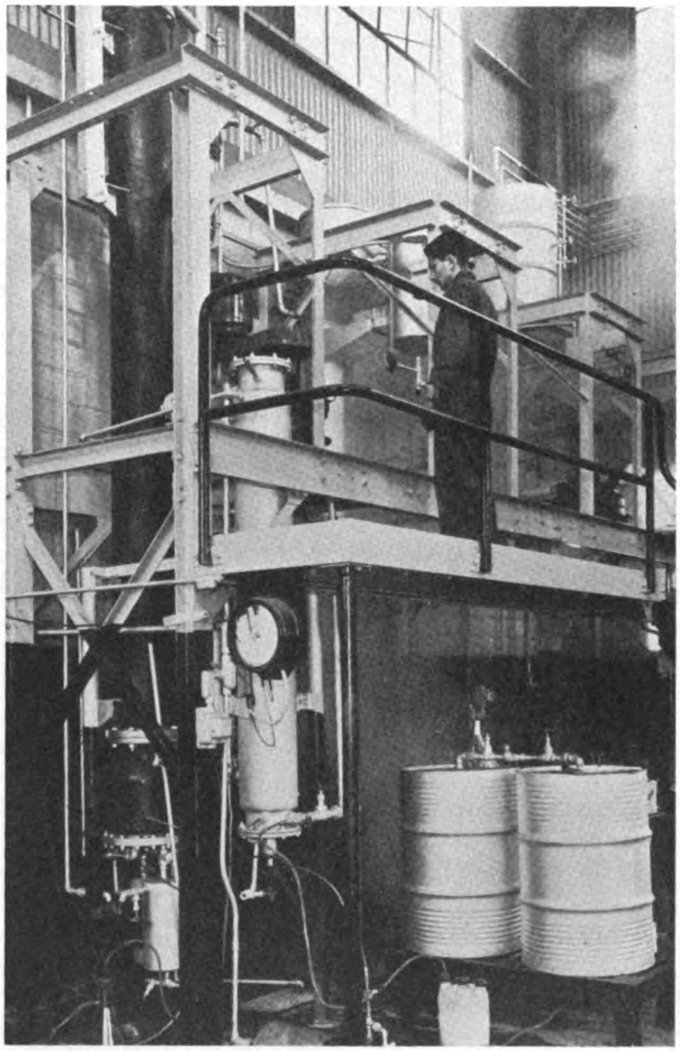

FIGURE 94.—Pilot Plant for Manufacture of Chemicals from Petroleum, Emeryville Laboratories, Shell Development Company Emeryville, California

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[15] Easterwood, Henry W. Manufacture of phosphoric acid by the blast furnace method. *American Institute of Chemical Engineers, Transactions*, *29*, 1-20 (1933).

[16] Curtis, H. A. The manufacture of phosphoric acid by the electric furnace method. *American Institute of Chemical Engineers, Transactions*, *31*, 278-95 (1934-1935); T. V. A. makes H_3PO_4 electrically at Wilson dam. *Chemical and Metallurgical Engineering*, *42*, 320-24 (June 1935); Making concentrated superphosphate at T. V. A. fertilizer works. *42*, 488-91 (September 1935); The air-nitrogen industry at home and abroad. *33*, 408 (July 1926); Curtis, Harry A., Miller, Arthur M., and Junkins, J. N. T. V. A. estimates favorable costs for concentrated superphosphate—II. *43*, 647-50 (December 1936); Curtis, Harry A. Re: Phosphoric acid costs. *44*, 75 (February 1937); Curtis, Harry A., Copson, Raymond L., and Abrams, Armand J. Metaphosphate investigation aims at cheaper fertilizers. *44*, 140-142 (March 1937); Curtis, H. A., Miller, A. M. and Newton, R. H. T. V. A. reviews its experience in phosphate smelting. *45*, 116-20 (March 1938); Process developments at T. V. A. phosphoric acid plant. *45*, 193-97 (April 1938); Curtis, H. A., Copson, R. L., Abrams, A. J., and Junkins, J. N. Full-scale production of metaphosphate achieved at Wilson dam. *45*, 318-22 (June 1938); Curtis, H. A., and Heaton, Roy C. Design for a phosphate furnace. *45*, 536-40 (October 1938).

genation and other catalytic processes that have aided in the development of modern aviation fuels, synthetic rubber, and similar products from petroleum. The achievements of these four companies, all of which are large employers of chemical engineers in their research and development departments, are cited here because they are typical of the progress that has been made since 1929 by many other process industries.

Economic and Commercial Research

Very early in the development of any chemical product or process, someone must answer to management's satisfaction several simple but soul-searching questions, such as: "Is it feasible? Can it be made commercially? About what will it cost? Where and how much of it can be sold?"

This preliminary appraisal of a research project is often a chemical engineering function and responsibility. It has been pointed out by Dr. John H. Perry [17] of the du Pont Company that a competent chemical engineer of broad experience and sound business judgment can often do more to promote the economical development of new products than almost anyone else in an industrial organization. If through preliminary feasibility studies, it is possible to weed out the projects that could not possibly yield a fair return on the necessary investment in research and development, a great saving can be effected. In like manner, it is often possible to apply similar studies to choice of raw materials or to alternative processes well in advance of laying out a research program.

In some of the larger chemical companies, these feasibility studies are made by a separate division of the development department devoted to chemical engineering economics. Such an agency collects and interprets data not alone from research but also from production and sales departments. When a problem is presented, it must correlate all the known or estimated factors (economic, technical, medical, legal, financial, and public relations) and arrive at a convincing answer on which management can base its most important decisions.

Another type of economic research is of an exploratory nature. Instead of waiting to have new ideas originate in the research department, the chemical engineering scouts search out opportunities from the field by studying consumer needs and the competitive situation as regards supply and demand. They often initiate negotiations for licensing of patented processes and carry on other functions in advance of the regular research program.

It would be a mistake, however, to imply that feasibility studies are confined to any preliminary stage of research or development work. As a matter of fact, much of the work of the chemical engineer in the pilot plant is concerned with the feasibility of equipment and processes as determined by comparative yields, performance, and costs. Economic balance also enters into the selection of proper materials of construction to resist corrosion, heat, or abrasion, and of adequate packaging and shipping containers. In short, what Dr. Little meant by the "introduction of the dollar sign into the chemical equation" calls for a high order of chemical engineering economics all along the line.

In recent years many of the scientific principles and practices long applied to research and production have been extended into the field of marketing and distribution. As a result there has been an increasing demand for chemical engineers in sales-development work.[18] Market analyses and sales studies designed to find new outlets for new or existing products are being made constantly by well-staffed departments in many companies. Closely allied with men in such departments are employees engaged in customer research or in technical service work carried on to study the problems of the consumer and assist him in the use of proper materials or equipment.

Market analyses and technical service may seem somewhat remote from chemical engineering, yet both form important parts of the successful program of research and development. As a matter of fact, much of the success of chemical industry in recent years has resulted from the fact that its research has been conducted on an engineering basis from the first selection of the project to the final utilization of the product in the plant of the customer.

What Lies Ahead?

Despite the remarkable progress that has been made in the application of chemistry in industry through modern chemical engineering developments, much remains to be done. Our present knowledge of the theoretical principles underlying many of the unit operations is fragmentary and far from satisfactory. Even our empirical knowledge, painfully gained through costly trial and error, often proves entirely inadequate because we lack quantitative measures of performance under varying conditions. From the standpoint of theory, there is a better understanding of the underlying thermodynamics and reaction kinetics of many of the unit chemical processes; yet in practice the yields obtained in many organic chemical industries are still

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[17] Perry, John H. But is it feasible? *Chemical and Metallurgical Engineering*, 43, 75 (February 1936).

[18] Tyler, Chaplin. Chemical engineering economics. New York, London, McGraw-Hill Book Co., Inc., 2d ed., 1938.

pitifully low. More fundamental research is sorely needed, if these industries are to reach the same high level of chemical engineering efficiency that is common practice in many of the inorganic fields.

A symposium on "Unit Operations Appraisals," published in May 1934,[19] included a series of technical "balance sheets" in which the known assets of fundamental data were set down alongside of corresponding liabilities. For heat transfer, flow of fluids, distillation, evaporation, and drying, there was an impressive array of facts and figures on the assets side, balanced against somewhat fewer but still serious liabilities. In the case of mixing and agitation, absorption and adsorption, filtration and other mechanical separations, there was an overbalancing list of liabilities—of facts and data yet needed to give a true understanding of underlying theory.

Some progress has been made by chemical engineers in transferring such liabilities into assets during the past 6 years, but there are still too many gaps existing in our theoretical knowledge of the unit operations as T. H. Chilton has clearly shown in his Chandler Medal address[20] and in a summary of unsolved problems which he presented before the Chemical Engineering Division of the Society for the Promotion of Chemical Engineering Education in 1938.[21]

Apart from this fundamental study that is so necessary and important, there is still a great opportunity for future rewards to those who will carry chemical engineering research and development into the older industries that have been slow to accept this relatively new technology. Food-processing, leather, and textile operations represent promising fields for this type of cultivation. The transformation that has been effected in petroleum refining and coal processing, for example, can be duplicated in certain other industries, once their problems are subjected to sound research and the results applied through efficient engineering developments. In this process, the chemical engineer is destined to play an increasingly important role. The late John Hays Hammond expressed this view in these words:[22]

> Chemical engineering, more than any other, may be called the engineering of the future. . . . The chemical engineer stands today on the threshold of a vast virgin realm; in it lie the secrets of life and prosperity for mankind in the future of the world.

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[19] Symposium of unit operations appraisals. *Chemical and Metallurgical Engineering*, ***41***, 232 ff (May 1934).

[20] See footnote 19.

[21] Chilton, Thomas H. Timely research problems in chemical engineering adaptable to universities and colleges. *Industrial and Engineering Chemistry* (*News Ed.*), ***16***, 417–21 (August 10, 1938).

[22] Jackson, Dugald C., Jr., and Jones, W. Paul, editors. The profession of engineering. New York, John Wiley and Sons, Inc., 1929, pp. 114–16.

SECTION VI

7. INDUSTRIAL RESEARCH IN THE FIELD OF ELECTRICAL ENGINEERING

By Dugald C. Jackson and Harold B. Richmond

Professor Emeritus, Massachusetts Institute of Technology, Cambridge, Mass.; and Treasurer, General Radio Company, Cambridge, Mass., respectively

INTRODUCTION

This report is divided for convenience into three sections individually dealing with: (1) The evolution of industrial research in the electrical engineering field, (2) the current activities of such research in this field, and (3) the promise of results which lie with industrial research in the field. In considering this question of industrial research and the qualities of its contributions to the welfare of our population, it will be helpful to keep in mind the order and nature of research processes, which are in categories somewhat as follows:

(*a*) Some individual thinks out and in concrete terms proposes a desirable objective of research, which in the electrical-engineering field may relate to producing an improved means of communication, a more efficient process in electric-power generation or transmission, a device to perform a task previously unaccomplished, some means for preventing some type of apparatus fault, or any one of many unsolved items of importance; or it may relate to something far more fundamental that possesses the possibility of leading to revolutionary inventions if the research discloses additional facts regarding natural phenomena which may be given serviceable application;

(*b*) One or more individuals, stimulated into action by this idea, make critical observations, measurements, and calculations which throw new light on the problem being considered and ultimately provide data indicating the desirability or probable uselessness of continuing the investigation and inquiry in an exacting way to its limit;

(*c*) If the efforts in category (*b*) indicate the desirability of proceeding, and financial support may be relied on for further research, a suitable group of engineers, scientists, and artisans may be set to work in extending the observations, measurements, and calculations, in which performance it may be needful to conceive and put into effect new processes of measurements and calculations, and to design, build, test, and modify for retesting new apparatus or products. This may be pressed forward until a useful new or improved result is achieved, or until failure of the particular attempt is admitted.

It will be noted that industrial research is an active process intended to yield new products and benefits. When successful in this intent, it expands the opportunities for employment in the manufacturing and operating industries. Inasmuch as the process is based on hope and requires the expenditure of time and money in advance of any assurance of a return in compensation for this effort, it is notably dependent on the courage and enterprise of men of ideas who are willing to risk their time, their money, or both in the hope of a profitable result for the adventure.

Experience in the repetitive processes of making things usually will gradually disclose methods for lessening the labor of making the particular things or for lessening their cost, even without the benefit of exacting research. But the gradual exhaustion of natural resources tends to make the procurement or production of some things more difficult or expensive, and the level of general living is likely to decline unless improvements and new products and processes can be discovered which may offset the declining situation. It is in this matter of disclosing improvements and discovering new products and processes that industrial research has proved itself so serviceable to the people of the United States. With adequate research wisely prosecuted we may expect continuously to develop an enlarging variety of improvements and of new products and processes (in whatever field the research is carried on) which confer new conveniences on the public, arouse new demands, and (through the need for production to satisfy the demands) cause an expanding market for labor. In this way, research proves itself to be an important national resource for the purpose of first maintaining and then raising the level of living, and for expanding employment for those who desire to be employed.

The aim of this report is to show briefly what industrial research in the electrical-engineering field has done, is doing, and may be expected to do—and why it should be generally recognized as a national resource; as well as how the many engineers and special scientists engaged in the work contribute to maintaining the resource. In consideration of the limited space available for the report, it has been thought best to refrain from using statistical expositions or charts.

Evolution of Industrial Research in Electrical Engineering

Electrical engineering roots in the discoveries of Humphrey Davy, Michael Faraday, André Ampere, Clerk Maxwell, Joseph Henry, and their contemporaries; H. von Helmholtz, Wilhelm Roentgen, Heinrich Hertz, and their contemporaries; and, in and near our day, Henry A. Rowland, J. J. Thomson, Lord Rayleigh, Lord Rutherford, together with many contemporaries of distinction as well as many men still creatively active in physical science.

These men have engaged in research for the purpose of identifying natural phenomena and seeking out their relationships, and they usually have worked in laboratories supported in educational institutions or in endowed research establishments. They seldom have given direct attention to useful applications of their discoveries. Other men, industrially minded, have followed up and continue to follow up the fundamental discoveries, producing further discoveries and establishing inventions through which the discoveries have been made useful—that is, through which the discoveries are made to contribute to comfort, convenience, and safety of human life.

The earlier of these industrially-minded men usually worked as individuals, gathered assistants about them, and ultimately built up an industry or industries of importance around their inventions when competent fortune was with them. Notable examples are Werner von Siemens, of Germany; Z. T. Gramme and others, of France; Paul Jablochkov, of Russia and France; Guglielmo Marconi, of Italy; John Hopkinson, Lord Kelvin, S. Z. Ferranti, and others, of Great Britain; Alexander Graham Bell, Charles F. Brush, Thomas A. Edison, Elihu Thomson, Edward Weston, Lee De Forest, Frank J. Sprague, William Stanley, George Westinghouse, Nicola Tesla, and contemporaries, of the United States, plus many men who are now active.

Out of the situation thus described have stemmed most of our now comprehensive processes for quick electric communication of intelligence by wires and radio; electric-power generation, transmission, and distribution; electric-power utilization in industry and in the household; electric illumination; electrometallurgy; electrochemistry; medical services of electricity such as X-ray treatments and diathermy; and other applications that pervade nearly every walk of life and most industries.

It is to be remembered that research in the sense here used consists of the processes of identifying additional facts among the phenomena of nature and of discovering hitherto unknown interrelationships between such facts—that is, it is research within the scope of the natural sciences. Industrial research has for its objects the formulation of improvements in the useful applications of natural phenomena or in discovering new applications of such phenomena. Industrial research therefore may involve fundamental investigation relating to phenomena in the hope of disclosing important basic discoveries which thereupon may be directed toward useful applications, as well as directing investigations toward usefully applying hitherto known phenomena. Industrial-research laboratories usually work in this broad field.

An industrial concern that has been born out of the womb of research is likely to maintain its growth by contributions from research; making of research, as the concern grows, a coordinated division of the total organization. This has been notably the result in the electrical-engineering field. The Edison Electric Light Company, the Thomson-Houston Electric Company, the Brush Electric Company, the Sprague Electric Railway and Motor Company, and lesser concerns, now joined together as the General Electric Company, center enormous activities around a great, productive, highly organized central research laboratory and a number of collateral laboratories, presided over by engineers, inventors, and discoverers in various special sciences. The like is true of the Westinghouse Electric and Manufacturing Company, the American Telephone and Telegraph Company, the great broadcasting companies, and a host of smaller manufacturing and operating companies, within the electrical-engineering field.

It is out of that process that came the following many features which are constantly in our lives:

The telephone system competent for use as a general social instrument, which contributes to intimacy in the communities and to unity of the Nation;

Electric illumination competent for use equally in homes, factories, and outdoor areas, through which added hours of comfort, convenience, and safety have been conferred on life;

Electric heating competent for use over the extraordinary range from heavy electrometallurgical processes to personal uses in the home;

The radio broadcast competent for daily recreation and aid in education of the families of a nation and for exchange of news between nations;

The control, protection, and conversion of generated electrical power which make such power competent for use in almost any walk of life;

And a multitude of other effects that have brought electrical devices and electrical influences in a wide way into the lives of citizens, through uses in their homes, in their facilities of transportation, and in their places of employment.

The generation and transmission of electric power in the abundant way which is characteristic of the present day are largely the outcome of long-continued industrial research. Some of the later applications of electric power to the purposes of transportation may be ascribed to industrial laboratory research; and so on through the electrical-engineering arts.

The Consequences of the Evolution

Industrial research and the accompanying discoveries and inventions in the electrical-engineering field have been constant contributors to the comfort, convenience, and economy of living, and at the same time have contributed to health, productivity, contentment, and happiness in the Nation.

Through such research and inventions, the standards of quality and the cost of telephone apparatus and plant have been so improved in two-fifths of a century that telephone service has been changed from the status of a frequently used business instrumentality and a home luxury to the status in this country of a commonplace essential of business and of a family utility which vies with the automobile in popularity.

In the automobile itself, the same processes of organized research, discovery, and invention have, through the electric means for starting, ignition, and lighting, contributed much to the attractiveness of that vehicle as an agency of transportation and recreation.

FIGURE 95.—Assembling of Million-Volt X-ray Unit, General Electric Company, Schenectady, New York

Electric lamps are notable examples of the results of industrial research in the electrical-engineering field. They are the direct offspring of industrial research and its associated discoveries and inventions. The economy of present-day artificial illumination is a monument to the process. For example, during the last third of a century research and invention relating to the ordinary incandescent lamp have resulted in more than doubling the output of light per unit of electrical energy expended, while the cost of lamp units for general use has fallen to a fraction of the former figures, and incandescent lamps (with their safety, convenience, and satisfaction for the home, office, store, and factory) have in this country substantially displaced the cruder and less safe illuminating agents of previous generations. During the same period, the price of electric power per kilowatt-hour has steadily fallen as a consequence of the same influences, but not to so large a proportion.

Such examples can be carried on to a multitude of instances. Even pressure vessels like high-pressure steam boilers and hydraulic penstocks are more economically made by using electric welding (a product of research and invention) in substitution for the older method of riveting. But space does not justify further illustrations. Industrial research in each decade is primarily concerned with the conditions of that decade, as well as being earnest with anticipation and prevision for the future. Therefore the foregoing brief review of the evolution during former periods must suffice for the description of past conditions.

Analysis of Our Current Activities

We will now turn to those present-day activities which are notably characterizing industrial research in the electrical-engineering field.

Measurements

An industry is not at full stature until it possesses precision instruments for the measurements with which to guide its industrial processes, nor is a nation in full stature as an industrial nation until it is competent to design and manufacture all precision instruments needed for use in its industries, both as working tools for measurements and as precise control standards. The problems of standards of manufacture and precise standards in methods, and in instruments for measurements, have proved worthy of extended research. Electrical engineering has been fortunate, since (springing as it did from strictly scientific grounds) logical units were early derived and methods of measurements were set up. An early committee of the British Association for the Advancement of Science was a pioneer in this respect. At the present day, levels of precision in electrical measurement challenge the precision of measurements available in every other field of science or engineering. Out of the early work grew the manufacture in the hands of von Siemens, Carpentier, Weston, and others, of accurate electrical measuring instruments for general use; and now the mission of filling the market demand for electrical measuring instruments, of both refined and commercial precision, has become an important industry of itself.

To produce these results, close association has been necessary among electrical engineers, physicists, metallurgists, physical chemists, and other specialists, in a manner readily secured in a well-balanced industrial research organization. Advances in all fields of science and engineering require new instruments of types and precisions adapted to the needs of advancing frontiers. The industrial research of electrical instrument makers has broadly fruited in showing the way for producing new types of instruments, and in improving the precision while reducing the cost of older types.

Progress has depended upon finding or producing new materials for this use and also upon learning how to use existing materials better. Examples of these paths of progress are to be observed in new alloys, such as alloy metals of special electrical qualities or of very high magnetic permeability and low coercive force and others of very high coercive force; in new insulating materials (dielectrics); in modifications in the forms of parts and modifications of materials themselves introduced to improve instrumental torque; in the manufacture of permanent parts by molding or die-casting so as to reduce costs and improve reliability; and in many other details.

Recently, entirely new fields of measurement and of equipment control have been opened up by the introduction of electronic devices, which have brought into the zone of practicability types of measurements previously unattainable, and likewise have made control methods more economical and convenient for various electrical devices. The photoelectric effect has been discovered and brought into a multitude of uses in measuring and controlling devices. These improvements have also facilitated telemetering and accompanying processes of remote control in a variety of situations.

The recent rapid march toward use of ultrahigh-frequency currents in the radio and associated fields has imposed on the laboratories a big responsibility which they have met admirably by developing new or modified methods of measurements adapted to the circumstances. These make possible measurements of satisfactory precision in parts of the electric-wave spectrum previously untouched. The use of piezoelectric crystals as standards of frequency and time, and the development of a whole family of equipment for precise frequency and time measurements, have come out of the industrial laboratories in quite recent years, and have supported the practicability of notable advances in the communications art, such as narrow-frequency control for radio frequency bands, picture transmission, and the rudiments of television.

Electrical Communications

Our greatest systems of electrical communications are legitimate children of the industrial research laboratory. Alexander Graham Bell, aided by Thomas A. Watson, was at work developing harmonic (multiple) telegraphic apparatus when he discovered the principle of telephony and produced the first transmitters and receivers. Other able men came into the field to make discoveries and inventions, and organized research became more and more productive, until research laboratories supported in the electrical-communications field became established in many parts of the world. The laboratory of the American Telephone and Telegraph Company (the Bell Telephone Laboratories) is the most extensive and important of them, but there are several other very notable American laboratories in this field.

Ocean telegraphy through submarine cables was made a success and improved similarly. The genius

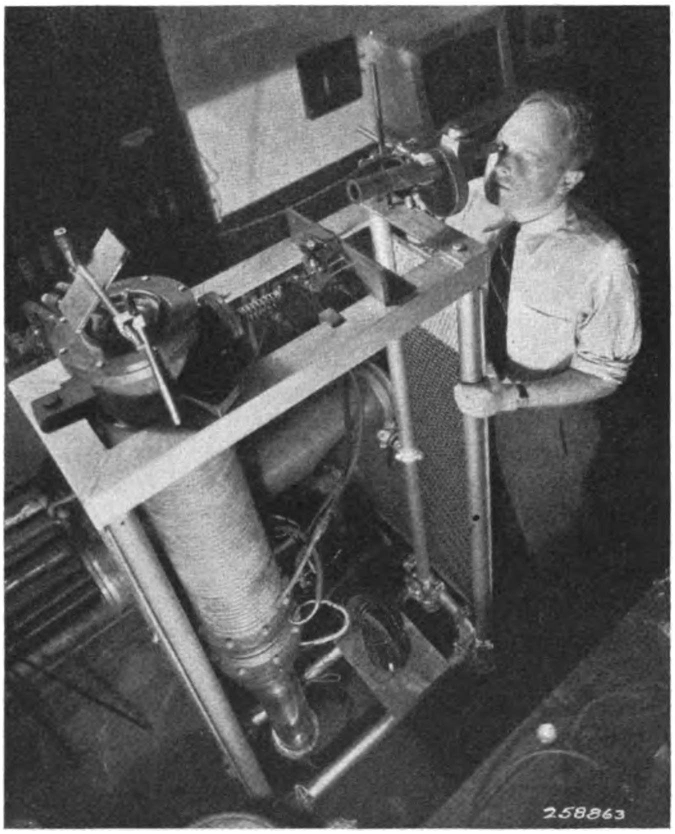

FIGURE 96.—Vacuum Electric Furnace for Production of Single Crystals of Gold and Copper. Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania

in mathematics and physics and their applications of Lord Kelvin (then Sir William Thomson), with the aid of other competent men, guided the promoters and manufacturers to improved processes of manufacture, improved processes of laying deep-sea cables, and improved methods of testing them. Moreover, they invented unique new instruments for sending and receiving messages. It was this process of industrial research dedicated to the purpose of scientific discovery and invention which, in spite of the early failures of cables, made ocean telegraphy a success and has continued to contribute improvements. Land telegraphy has likewise profited, and is profiting, from such organized industrial research.

Radio telephony and telegraphy are other extraordinary results of industrial research. Following the hint inherent in the electromagnetic-wave experiments of Heinrich Hertz, Marconi began his effort to apply electromagnetic waves to wireless communications. When he transferred his work from Italy to Great Britain, a research organization was gathered together to press forward the applications, which met with so much success that similar laboratory organizations entered the field in various parts of the world. Several of the most important of these, including that of the Radio Corporation of America, now are located in this country.

The addition of the triode-vacuum tube of De Forest, and great inventions by others, brought corresponding processes into the field of telephony with wire circuits, with extraordinary results in improving telephone service and lowering the prices necessary to be charged to users of such service.

The numerous improvements have so bettered the service and lessened the cost of telephone and telegraph service that in this Nation the public has profited in multiple degree for all the large expenditures put into the telephone and telegraph researches; in addition to the individual citizens having gained so much in convenience and in recreation from the wire and the radio communication systems.

Active research continues in many industrial research laboratories associated with the communications art, with the result that scientific discoveries and inventions are leading to further improvements. Recent advances have added materially to the national economy and to opportunities for national recreation. New telephone-transmission channels have been secured through the use of high-frequency carrier currents, and recently the so-called "coaxial" cable has been added. Increased speed of transmission, increased numbers of usable transmission channels in a circuit, and decreased cost of plant have been produced as the results of newly discovered materials (such as magnetic alloys and improved insulations) and from better understanding of the electrical properties of materials and of electric-circuit combinations. Thereby the quick transmission of intelligence has become a relatively low-cost product, associated with all the favorable implications of mass distribution of such a powerful influence as electrical intercommunications for producing unity throughout the population.

Specifically in the telephone field, research has resulted in (and is continuing to provide) economy of installation and operation through the effects of improved cable facilities, carrier and broad-band systems of transmission, better understanding of transmission phenomena accompanied by improved structure of circuits, switching methods, insulating materials, vacuum-tube design, the utilization of piezoelectric crystals for electrical filters and for standards of frequencies. This not only is contributing new techniques to improve service and decrease prices for local communications, but also is promoting speed and economy of communications over long distances.

In the radio-broadcast field important research is progressing in various lines among which we may note the effort to overcome disturbing effects caused by "static" and other extraneous noises. Progress of particular promise is shown in what is known as "frequency modulation" and "phase modulation," and combinations thereof, and these results may contribute great improvement to the quality of broadcast reception. Such associated important radio procedures as route and landing guides for airplanes and other radio-wave applications are the outcome of long and intensive laboratory research; and constant extension of such service is observable.

In the oldest field of wire communication, namely, wire telegraphy, the developments have particularly taken the form of improved factors governing speed of transmission, increased utilization of wire plant, and extension of wire facilities for additional uses such as picture (facsimile) transmission and the use of teletypewriters, with the printer-telegraph system made capable of use on a toll basis.

In general, industrial research in the electrical communications field has been of a basic character relating to circuit theory and to circuit networks which apply to steady-state conditions of the currents, transient conditions, and line transmissions; and also to the prevention of interference between circuits within the communications field, and between high-voltage power circuits and communications circuits; to means of shielding circuits, the invention of repeaters and their introduction into the operating circuits, and to mechanical acoustic systems. Basic studies of materials, particularly of magnetic and electric materials, have brought great fruit from the work carried on in the communications laboratories, and those laboratories of themselves may be cited as exemplars of industrial research as a national resource.

Such laboratories, besides producing new and desirable results of commercial utility, even touch upon the conservation of natural resources which are expendable. Continuous and helpful studies are made of the conditions of, causes of, and means for combating decay of wooden poles and cross arms used to support overhead wires, the corrosion of metallic wires and metallic devices, the protection of cable protective sheaths from corrosion by electric currents in the earth, and from other such deleterious effects. Even the character and quality of the tools and implements used in manufacturing apparatus and in the construction of plant have been and are being subjected to research, with advantages derived through improving the accuracy and speed of manufacture and the ease and safety of installation.

In the field of electronics, which now has so great an influence in electrical communications, research has included and still includes many features of service and promise besides those already referred to, such as: Electron optics, especially in relation to television, but finding application in electron microscopes and other devices, and thereby opening new vistas for industrial physicists; properties of coatings for television tubes, with a side contribution to the production of high-efficiency fluorescent lamps; controls through photoelectric cells for various situations; medical aids through diathermy; electron multipliers and allied devices; new types of oscillators, which come into a multitude of services.

In the field of radio communications, development of the use of ultrahigh frequencies is receiving emphasized attention, and radio waves of frequencies above 30 megacycles per second are being given useful applications in such relations as police communications, harbor-craft communications, airplane communications and airplane guidance, urban broadcasting, governmental communications, television, and facsimile broadcasting. How far these developments can go is still for the laboratories to determine, but it is worthy of comment that even some extremely high-frequency waves, often called "microwaves" because of their short lengths, show promise of utility. New types of vacuum tubes are being developed to accompany such service.

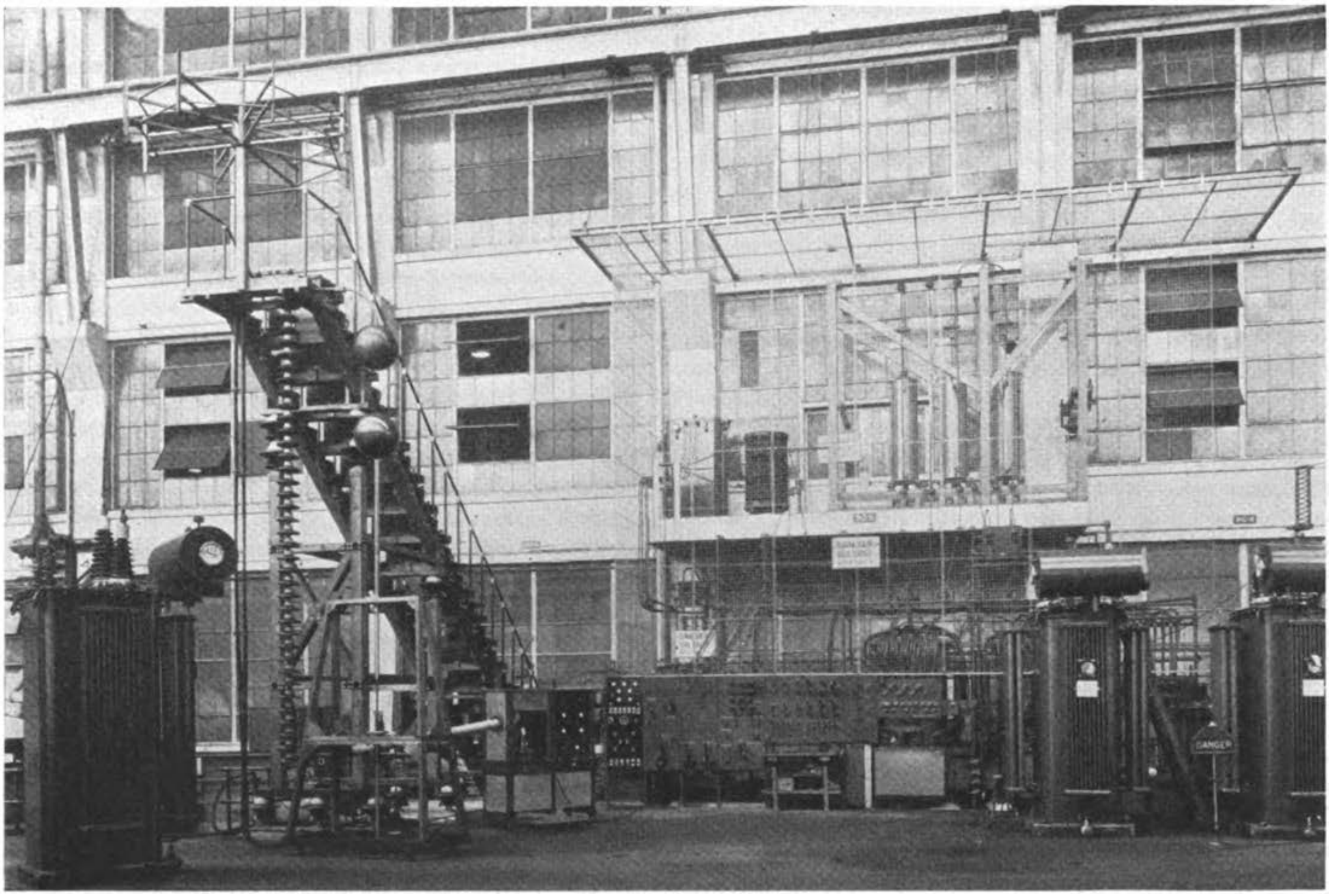

Figure 97.—Surge Generator, Wagner Electric Corporation, St. Louis, Missouri

The development of television processes is receiving very intensive attention in the laboratories, in the expectation of raising its commercial utility. The same may be said of facsimile transmission, to the improvement of which, as concerns the quality of received pictures and speed of sending and receiving, the laboratories are giving active attention.

Electric Illumination

Artificial illumination has been a need of mankind since prehistoric man began to use burning brands for torches. Indeed, demand by mankind for artificial illumination is so great that we may justly refer now to such illumination as a necessity for comfort, convenience, and security. The characteristics of electric illumination are of so desirable a nature that its importance is outstanding compared with other means for artificial illumination; and we are indebted to industrial research for its development. That is, electric illumination, like electrical communications, is strictly the child of industrial research.

Arc lamps arranged with individual mechanisms which made many lamps operable in series in constant-current circuits, and incandescent lamps constructed somewhat as at present (i. e., consisting of a hermetically sealed evacuated glass bulb containing a mounted filament of conducting but high-resistance material, and leading-in wires sealed in the glass to enable electric current to be carried to the filament), were both originated near the opening of the fourth quarter of the nineteenth century. The arc lamp referred to was the invention of Charles F. Brush and the incandescent lamp the invention of Thomas A. Edison, each one as the consequence of experimental investigation directly aimed at the result ultimately accomplished. Various inventors had preceded Edison and Brush, but had not brought their researches to the point of successful invention.

Many able men entered the field after the successful inventions were made known, with the result that great laboratory activity grew up and has continued for the improvement of electric illuminating devices. The Brush type of arc lamp has been largely displaced by better means for illuminating areas for which the early arc lamps were adapted, and the incandescent lamp has gone through a series of extraordinary improvements. Collateral research has resulted in additional and special types of electric lamps, such as the so-called mercury-vapor lamp, the neon tube, and fluorescent lamps which are already in considerable use and which hold great promise for future improvements. The result has been to produce safer light, more illumination for given money expenditure by the users, protection of the eyesight of those who read and study, and greater safety for those who work or move in hazardous situations which are not well lighted by natural means.

The researches securing these results are the joint efforts of physiologists, physicists, chemists, and engineers, sometimes working individually, but commonly working in harmonious cooperation. From Mr. Edison's most active days to the present time, industrial research laboratories have intensively dealt with the scientific problems of illumination per se and with measures for providing effective illumination by means of devices (lamps) that convert electrical energy into light.

The outcome of industrial research in the field of ordinary illumination has given us improvements in three categories:

(1) Improvements obtained through better knowledge of the relations of lighting to seeing. Here are problems of physiology and psychology added to problems concerning the arrangements and types of lighting devices, all of which are features of laboratory research. The effects of eye-fatigue, elimination of glare, and the relations of brightness and contrasts all come in, as also do the problems of getting the light where it is most needed. The latter involve investigation of many types of light sources available for use in electric lighting, their adaptation to specific situations, and the adaptation of reflectors and lenses.

(2) Safety problems associated with illumination also come into the purview of industrial research, from the results of which directions may be formulated for applying light so as to reduce or eliminate hazards where hazards might exist.

(3) The cost of lamps and of illumination have been notably reduced as an outcome of research, and therefore the conditions for users have been improved.

Lamps themselves have been completely revised as the result of research. The carbon filaments of Edison and Swan have changed to filaments of the metal tungsten, and this of itself was accomplished only after long and exhaustive research. One problem was to produce from reputedly nonductile tungsten an extremely fine-drawn filament. The highly exhausted bulb of Edison has become a bulb still highly exhausted of its air but then modified by the introduction of nitrogen and argon or corresponding special gases. These and other changes of our ordinary incandescent lamps effected as the result of exacting industrial research have brought the lamps to many times the efficiency as converters of electrical energy into light as compared with the efficiency of the original Edison lamps of 60 years ago. Furthermore, lamps are now made that have individually much greater light output than Edison found it practicable to make even in his later days of lamp manufacture.

Associated with these changes, research has shown the way to design improved and more accurate processes of making the lamps and improved tools for carrying on the processes, so that the prices of lamps to the purchasers have been greatly reduced. This price reduction has amounted in round numbers to 60 percent in 20 years. With a consumption of normal size incandescent lamps (i. e., excluding miniature lamps and special lamps) amounting to over a million and a half lamps per working day, the annual money-saving to light users resulting from lowered lamp prices and improved lamp efficiencies that reduce the consumption of electric power far outweighs the annual cost of the research carried on to secure the results, while there is promise of further favorable results from continuation of the researches.

The average price of electric power used for lighting has gone down during the past 20 years, and the tendency of users has been to increase the amount of light provided. This comes to pass by the use of more lamps and the use of lamps of larger light output. But even thus we have not reached a sound level of general-purpose illumination at night. This objective may not be reached until research has shown how we may produce and use lamps of other and still more efficient types in general service.

Research has also aided in the production of lamps of special types which are now available for many purposes, some of which were previously mentioned, as well as special lamps available for special purposes. Examples of the latter are lamps rich in ultraviolet radiation for use in medical treatment and in sterilization and irradiation operations of various kinds; and lamps rich in the infrared (or heat) radiation, which have multiple uses in industry for heating and drying and are also of therapeutic value for heating in the instance of some human diseases. Research in the special types of lamps has also resulted in the production of a variety of lamps for decorative and for advertising purposes. The application of special light sources to stroboscopic, rapid photography is itself contributing to more convenient study of many industrial processes. All of these are in addition to the special vapor lamps, such as the mercury-vapor and sodium-vapor devices which are widely used in industrial lighting and highway lighting.

As the results of research are still bringing improved economies to the users of lamps as well as improving the adaptability of electric lamps to their purposes, still further favorable results of such research may be anticipated. As yet we have not even approached the limit of efficiency in the conversion of electrical energy into light, and there are great possibilities inherent for research here.

The Generation, Transmission, and General Utilization of Electric Power

Here again the successful results of today have been arrived at by the joint efforts of mathematicians, physicists, chemists, metallurgists, and engineers. Since the period some decades ago when electric-power delivery became an essential service in American communities, industrial research has been continuously applied in the effort to discover new processes and to improve the old so that the delivery of power might be made more uniform and reliable and the cost be reduced so that the price charged to the consumers could be accordingly reduced and the availability of the electricity increased. The effort has been rewarded by an extraordinary expansion in the use of electric power in this country.

Research has been intensive in this field and also of wide range, even though we omit from consideration the prime movers associated with power generation, which of themselves are, in their effectiveness, the outcome of much research.[1]

Electric-power research has extended from aspects concerned with the metallurgy of the steel cores of electrical machinery (to assure a suitable combination of magnetic and electrical qualities) to such matters as the protection of machinery and circuits from damaging attacks which may be caused by lightning—a very wide field. It has included both alternating-current problems and direct-current problems, and the conversion of one character of currents into the other; the cooling of electrical machinery by air, water, and hydrogen; the elasticity, plasticity, and creep of metals; the qualities of electrical insulating materials; the control and protection of electric circuits; electric arcs in both their useful and their destructive aspects; methods of testing machines and circuits; improvements for small motors; construction of silent fans; electrostatic air cleaning; induction heating; incremental distribution of loads between machines and between circuits; traveling waves; and many other features for which improvements obviously have been needed or regarding which it has appeared that research might disclose serviceable results. In some instances, however, research is undertaken because a particular field has not previously had exacting research attention and there appears reasonable promise of useful fruit to be gathered by such attention.

There are many manucfaturers of electrical machinery and circuit equipment in this country, several of

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[1] The outcomes of researches in the theoretical thermodynamics, the properties of steam at high pressures and superheated temperatures, the design and construction of large steam turbines and of high-pressure boilers have greatly advanced the art of electric-power generation from fuels.

them of very comprehensive importance. All the more important of these, and many of the lesser companies, carry on organized research, and important proportions of their products are formed on the results of the research. Many such concerns add to the range of their own research by cooperating with university laboratories or with special research institutions.

Ever since John Hopkinson, some 50 years ago, published the rational theory of the magnetization curve of the complex magnetic circuit of a dynamo, designers and inventors have struggled by experimental and mathematical research to find means for reducing the various losses, reducing the weight, reducing the bulk, and reducing the cost of electrical generators and motors per unit of output, and for improving their reliability. The features involved have related to ferrous metallurgy; the qualities of insulating materials; problems of heat flow and heat transfer for cooling purposes; problems of air resistance; problems of lubrication; problems of welding versus casting of frames; problems of stamping, slotting, and securing disks; and various other matters affecting the structure of such machines and the materials entering into them, besides the problems of adapting the machines to the service needs of users. The improvement of the product has been gradual and its extent is not fully realized by present-day users; but comparisons of generators and motors available 30 years ago with the present-day product show results that notably justify the intense work of innumerable able men and the large research expenditures. Space does not afford opportunity here to examine the matter in detail, but the fact stands forth that our present reliance on electric power as a national resource rests strongly on the improvements arising from this continuous research. Further research promises to disclose still further advantages.

Equally intensive and continuous research has characterized the field of circuits for the transmission and distribution of the electric power and the equipment associated with such circuits. Transmission voltages have been raised and reliability improved by researches in the field of insulation for both overhead and underground lines. Reliability of transmission has been secured by applying the results of research relative to transforming and switching devices, and the difficulties relating to "stability" for power systems have been greatly diminished by similarly intensive research. The safety of circuits for the distribution of the electric power on the premises of customers has been similarly established. The present voltage considered the upper limit for alternating-current power-transmission circuits has not far exceeded 220,000 volts. It is, however, contemplated using 287,000 volts on the lines from Boulder Dam to Los Angeles. What research may accomplish in raising this for the purpose of increasing the economical distance over which power may be transmitted, and what may be accomplished with high-voltage direct currents, have not yet been disclosed by the researches now under way.

Methods of testing machines and circuits in situ have been developed; and coordination of insulation is studied for the purpose of improving reliability of the power systems, which associates with studies for improving the details of the system structures. The prevention of harmful effects of traveling electromagnetic waves on high-voltage circuits has received adequate attention, as have the problems of the most efficient distribution of incremental loads between generators and circuits. Many features of the physical strength of circuits and associated devices have required extended research. The problems of corona caused by electronic discharge between conductors have been grappled with for the purpose of preventing deleterious effect on insulators and insulating materials and avoiding excessive power waste on transmission lines. Metallurgical and mechanical problems relating to the electrical conductivity and the mechanical strength of the materials available for line conductors have received their proportion of research attention. Even the prevention of vibration of costly conductors erected in long spans, which vibration causes breakage from fatigue stresses, has called for attention by men familiar with the theories of vibrations and with vibration phenomena.

Intense lightning effects are characteristic of many zones in this country, and are natural to a greater or less degree in most parts. These have been the cause of much damage to high-voltage electric-power systems and of interruptions to service. Elaborate researches in the field of lightning phenomena, the characteristics of lightning, and means for preventing damage to electric systems by lightning strokes have enlarged, and are still enlarging, our knowledge of these matters with the result that lightning protection of power systems is reasonably complete.

Insulated electric cables for high-voltage power systems are so important a factor that this subject is here assigned the next section for itself.

Insulated Electric Cables for Power Transmission and Distribution

The increasing voltage needed for the delivery of great bulks of power from urban power stations, and the reluctance of city governments to permit heavy circuits for high-voltage power to be established overhead in the streets, brought the problems of underground cables very much to the foreground. This imposed a major problem of research on the cable manufacturers and the power companies, which is related to the conductors and their mutual arrangements; the insulating materials, their qualities, and their arrangement; and the character of the protective sheaths for the cables and materials available therefor. Many manufacturers of cables, and power companies which are users of cables, have carried on such research. Some of this has not been of exacting scientific character, but much of it has been, and continues to be, highly commendable for its scientific character and the results produced.

As elsewhere in industrial research relating to electrical engineering, men of a variety of learning and skills have been needed for, and have participated in, cable research. On account of the materials to be used and their structural associations, the researches have called on chemists, physicists, metallurgists, mathematicians, and engineers. The problems to be attacked are atomic and molecular, electrical, physical (in the sense of structural), and chemical (in the sense of general and organic chemistry). Efforts are directed to discovering improved selection and arrangements of materials, to the improvement of cables of known types, and to the reduction of costs of manufacture, so that users may secure cables of higher voltage ranges, greater reliability, and longer life, and withal secure cables of the needed qualities at lower prices.

Cables may be made up with one conductor within a protective sheath or with several conductors within a common sheath, and may be used for a three-phase circuit, for example, with three single-conductor cables or with one three-conductor cable. Copper of high electrical conductivity is the approved material for the conductors of insulated cables, but the form of the cross-section of the conductor has some significance. However, the major problems of high-voltage cables relate to the insulation and its protection. Cables competent to transmit power of moderately high voltage (say 66,000 volts) came into some use early in the decade of 1920–30, and thereafter their use was extended rapidly. Cables for commercial power transmission have now been produced for voltages as high as 220,000 volts; but the problem of full reliability in service is still in the domain of research.

The materials now most used commercially or experimentally for high-voltage cable insulation are oil-impregnated paper of specific quality, rubber compounds, synthetic rubber substitutes, varnished cambric, free-oil and gas filling, the last two being associated with suitable separators for the conductors and with suitable supply tanks, and sometimes with means for maintaining a relatively high pressure in the tanks. Rubber compounds and synthetic rubber substitutes are usually confined to low-voltage conductors, as also are insulating coverings composed of asbestos, glass fabrics, and certain plastics.

The problems of heat conductivity, heat dissipation, and the safe temperatures for various insulating materials make disturbing relations as also do corona effects in unhomogeneous arrangements. The producers of refined petroleum oils and the manufacturers of certain resins and other chemical compounds have actively joined in the researches relating to the applicability of their products to cable and wire insulation.

Among the outcomes of research in this field are improvements in the methods of measuring the qualities of insulating materials and of cable insulations, and also in methods of periodically testing cables in situ to discover whether they are deteriorating. The latter, of course, is a preventive against deterioration being allowed to go to the point of insulation break-down and consequent interruption of the electric service at some moment of inconvenience for the power users, since the tests will show whether a cable should be replaced.

Protective sheaths composed of lead have long been a subject of concern because of their mechanical frailty and in certain circumstances their readiness for corrosion or fatigue. Research has not found a substitute but has pointed the way to eliminate some of the causes of weakness of lead sheaths and shows promise of discovering some improved lead alloy, or alloys, which may serve the purpose more satisfactorily.

While the great problems of electrical conductor insulation relate to the higher voltages used in power transmission, the annual expenditure in this country for insulated conductors to be used for low-voltage circuits on consumers' premises has led to active research by some companies in the effort to find more favorable compounds for the substance of such insulation materials. Considerable progress has been made of recent years, but apparently more may be accomplished.

Miscellaneous Applications

Innumerable commercial applications of electricity have been improved by the results of research which have not been referred to in the foregoing, just as innumerable details have not been mentioned specifically, although such details are within the fields discussed where industrial research has served importantly. For examples there are numerous household conveniences such as electric refrigerators, air-conditioning devices, and the like, which are the outcome of extended research.

Space does not warrant discussing these various features, but one special application commands mention, namely, electric welding. When Elihu Thomson introduced the resistance-welding process and de Meritens introduced the arc-welding process, these at first received relatively scant attention except for places where complete assurance of the integrity of a weld was not of primary importance. However, in later years, X-ray and corresponding methods of examining completed welds have been proved to be practicable and electric welding has taken an important place as a substitute for the riveting of pressure vessels and conduits, as a means for fabricating machine frames instead of using castings, in ship building, and in other operations.

The status of the electrical engineer in the welding field is peculiar because electrical energy and its application are only a small part of the whole problem. There has seemed to be less interest by the metallurgist, the chemist, and the mathematical physicist in the complex problems involved in welding research. It has remained for the electrical engineers and the mechanical engineers to coordinate this work in the promotion of better electric welding, although much electric-welding research is carried on outside of the scope of electrical engineering and is not referred to here.

In the general field of application, research in electric welding has followed the following closely related lines:

1. Residual stress studies.
2. Transient heat flow.
3. Chemistry of steel through the critical zone.
4. Means for assuring the integrity of welds.

Still more knowledge is required to permit a wider application in pressure vessels such as high-pressure steam boilers, where code authorities have set various limitations to avoid chances of failure. The accumulated knowledge of the reliability of results from electric welding has made possible savings in the costs of structures such as pressure vessels, high-pressure steam piping, stainless-steel rail cars, automobile bodies, elements of airplanes, ship frames and hulls.

In the equipment aspect of arc-welding, the most important project is that of improving the electrodes used in the processes. This is required not so much from the standpoint of adaptability, as because it is extremely important that the chemical reaction in the arc-welding process shall be that of reduction and not oxidation of the welding metal. This necessitates close control of the atmosphere around the welding arc, particularly to prevent the hot metal which has passed through the arc from coming in contact with the air until it has had time to cool. These electrode researches have resulted in an increased specific gravity of welds and tensile strength above that of the parent metal, and in a better control of the materials from which the wire welding-rods are made. Other means of preventing the welding area from being affected by oxidation have been invented for circumstances where the work can be brought to the plant instead of the welding equipment being taken to the work. An example is in what is known as atomic-hydrogen welding which was itself derived from an industrial research laboratory.

In the field of apparatus associated with electric welding, considerable research has been, and is being, carried on to improve the sources of welding currents through the use of electronic tubes of high power to replace the more cumbersome motor-generator units.

Future Promise

In each of the divisions heretofore discussed, it will be noted that important results from continuous research have been and are being achieved. It is important now to observe that in most of the fields the possibilities of industrial research are by no means exhausted. Indeed, greater results may be anticipated in the future than heretofore, as a consequence of continued prosecution of active research in the wide fields of electrical engineering. As labor-saving machinery is introduced to a greater and greater extent in the old industries for the purpose of reducing the cost of products, and the laboring population also perhaps increases somewhat, the encouragement of research as a national resource for developing new industries and new aspects of old industries becomes of emphasized importance.

The past and present cost of industrial research in the electrical-engineering field has been repaid to the users of electrical equipment and service in multiple degree by the reduced prices of products and services, their greater adequacy for their purposes, and the conveniences therefore conferred on the population of the country. With the conditions of increasing use of labor-saving machinery and the growth of the laboring population just referred to, the contributions which industrial research may make to national welfare are broadened in importance and the extension of such research deserves a generous national attitude which will reestablish the readiness of manufacturers to enter upon new industries and new aspects of old industries as a matter of adventure, supported by the hope of establishing permanent advanced steps from which additional opportunities for employment may arise and some financial profit may result.

Suitable industrial research also notably contributes through its results to the stability of existing manufacturing and operating industries, which gives a stabilizing influence on employment. Moreover, it is usual for industrial research laboratories to make early publication of novel results secured, resting reliance on the patent laws to protect the reasonable rights of the originators in the field of commercial development. For such publication there are journals of national professional societies in the electrical-engineering field and of societies associated with various special sciences. These journals are hospitable to research articles and to articles relating to science and to engineering inventions which originate with men of the staffs of research laboratories. The meetings of the societies provide forums for the discussion of research and the development of inventions. In some instances, the laboratory itself publishes a periodical journal with a high scientific standard and a wide circulation in electrical-engineering circles. In such ways, among others, information from the laboratories has come to be both promptly and widely disseminated. As a consequence, the industrial research laboratories have become in America among the most important distributors to the public at large of knowledge of sciences and their applications.

There is a sequence leading through problems of industrial research which it is needful to keep in mind because it consumes time. For illustration, Michael Faraday, besides many other great achievements, in the first third of the nineteenth century thought out and experimentally demonstrated the phenomena of electromagnetic induction and also outlined the conception of fields of force and lines of force. Maxwell thereafter synthesized such ideas by means of powerful mathematical treatment, thereby formulating the idea of electromagnetic waves in space. Hertz experimentally proved the truth of Maxwell's predictions regarding electric waves and provided means for producing and for detecting such waves in a range of wave lengths. The way was then open for the inventor, Marconi, to carry forward, and wireless communication of intelligence sprang into being as the child of his labors. This continuous sequence of events occupied over a century of active reflection and research for bringing modern radio broadcasting to fruition. Industrial research, such as that of Marconi and his associates and successors, means seeking, seeking, seeking for results on the basis of knowledge already abroad and fortified by additional knowledge which the effort of seeking may disclose. The latter, as a byproduct, often gives a lead into additional threads of useful research and applications.

Such is the character of time-consuming sequences that usually precede the great inventions from which influential industries arise, and industrial research must be maintained in the broad field extending from touch with basic discoveries in science to the final great and small inventions. A notable contribution to the speedy application of new knowledge to serviceable purposes is one of the characteristics of the industrial research laboratories, which promptly seize on each new discovery in science for the purpose of examining into its possible aid to human comfort and convenience. The length of period between original discovery and useful application is shortened by the processes of the industrial research laboratories.

In all of these industrial aspects in the electrical-engineering field, it is those trained in the basic features of the sciences and economics pertaining to the field, i. e., the electrical engineers, who are needed for leadership; and around them are gathered groups of men and women who are specialists in the various sciences. These groups are themselves a national asset when wisely guided, because they disclose the foundations of new industries and of improvements to old industries from which are secured wider opportunities for employment of many citizens and additional comfort, convenience, and security for the citizenship at large. Electrical engineering, including all of its power branches and its associated branches of illumination and communications, is a relatively new art. Revolutionary advances which have arisen within the field to the benefit of mankind are within the memory of mature adults, and hardly more than a beginning has been made. Industrial research in the field, guided by competently experienced electrical engineers, and liberally encouraged, therefore must be mentioned among the important national resources of the United States. Its further expansion may be supported with assurance of value to be returned to the national economy and of service contributed to welfare in our national life.

SECTION VI

8. INDUSTRIAL RESEARCH BY MECHANICAL ENGINEERS

By Harvey N. Davis and C. E. Davies

President of the Stevens Institute of Technology, Hoboken, N. J.; and Secretary of The American Society of Mechanical Engineers, New York, N. Y., respectively

ABSTRACT

This report describes the functions performed by mechanical engineering research skill in various phases of industry. The information in this report, obtained by correspondence from over 400 individuals in 55 different industries, reflects the views of industry itself about the part played by mechanical engineers in research and reveals the widely varying understanding of men in industry about the purposes and values of research.

The conclusions of the report are:

Many correspondents emphasize the difficulty of attempting to classify industrial research activities according to the particular engineering or other disciplines within which they fall or according to the particular academic training of those engaged in them.

While testing of raw materials, of work in process, or of finished product involves activities that are usually of a routine rather than a research nature, a considerable amount of true research is often found associated with or inspired by these inspectional activities.

Research with respect to the materials, equipment, methods, and processes of manufacture is one of the commonest and most important types of activity of mechanical engineers in industrial research today.

Development of better products and of new products is a second very important type of research. On it all progress in the essentially mechanical industries depends.

Opinions differ widely as to where, if anywhere, a line should be drawn between normal engineering design, engineering development work, and research. It is the opinion of the writers of this report that research activities and the research spirit and technique should be broadly, rather than narrowly, conceived.

Research, and particularly field-research, for new uses and new markets for old products is of the greatest importance.

Fundamental research, broadly defined as including data gathering as well as investigations of a more purely theoretical nature, is very common in industry, and is very often an activity of mechanical engineers.

Research in universities and engineering schools which is partly or wholly paid for by individual industrial clients or cooperating industrial groups constitutes an important part of the great volume of industrial research.

Management can well be thought of as a branch of mechanical engineering. It is certainly a type of work in which a great many mechanical engineers are engaged. It is a field in which much is being done that well deserves to be called research. It is a field in which much more organized research should be undertaken by industry.

The formal organization of a company's research activities varies widely as between companies of different sizes and amounts of experience in research, but not in any significant way as between different industries as such.

While the activities of public utilities seem to differ in kind from those of factories, the differences are probably more apparent than real, and the research activities of utilities are as diverse and important as are those of manufacturing establishments. Research in management is probably relatively better developed among public utilities than in industry generally.

The writers of this report suggest for the consideration of those interested in industrial research the thesis that everything that anybody in industry does in the course of his daily work is either routine or research. It is suggested that the universal acceptance of this thesis as a matter of definition would do much to clarify the thinking of industry with respect to the fundamental basis of its present prosperity and future security.

Introduction

Basis of This Report

The purpose of this report is to describe the functions performed by mechanical engineering research skill in various phases of industry. The wide usefulness of mechanical engineering research has made it necessary to secure aid from a surprising variety of industries. Information has been obtained from organizations belonging to 55 different industries ranging from iron and steel, power, machinery and tools, and motor vehicles, through chemicals, ceramics, electrical machinery, and petroleum, to food, clothing, amusement equipment, beverages, musical instruments, and insurance, and even large mail-order houses and department stores.

The approach to industry for this information was made by means of over 600 letters sent to executives in charge of research in selected firms, and to the members of the various research committees of The American Society of Mechanical Engineers. These letters were purposely phrased briefly, merely defining industrial research in the words of Dr. C. F. Hirshfeld as "organized fact finding of any sort that is financed by industry," and asking for "a brief statement of the research functions performed by mechanical engineers in your organization," even if "this fact-finding function in your company is not formally organized as a research laboratory." Because of this brevity, the material submitted is neither homogeneous nor exhaustive—a quantitative survey of industrial research is being undertaken by others—but also because of this approach many of the answers contain points of view, opinions, and side lights on research that might not have been elicited by more formal and meticulous questioning. Over 400 letters have come from members of more than 325 industrial and other organizations, the responses ranging all the way from "we are unable to cooperate in the matter referred to" to extended descriptions and stimulating essays on research, some of them in printed form. To all of the cooperating individuals and to the organizations they represent grateful acknowledgment is hereby made for their cooperation, which has often involved an expenditure of much time and effort.

Quotations from these letters form a considerable part of this report. For the purpose of clear condensation, the phrasing of the writer has not always been followed exactly, even in matter within quotation marks, for which liberties apologies are hereby offered; but it is believed that the meaning of the original writer has been preserved in all cases.

Distinction Between Mechanical Engineers and Others

One of the difficulties emphasized by many correspondents is that of distinguishing between "mechanical engineers" and other sorts of engineers, particularly chemical, electrical, textile, and agricultural engineers, and also between engineers, metallurgists, physicists, and certain types of chemists. One correspondent writes, "Thus it may be said that our industrial research performed by mechanical engineers covers a very wide field and a field which frequently overlaps, or which is coordinated with, research by chemical engineers along more clearly defined chemical engineering lines." Another writes, "It is quite impossible to differentiate mechanical from chemical engineering research in our organization." In another field, a research executive writes, "Our industrial research work is a mixture of mechanical, chemical, and petroleum engineering. From a management viewpoint, it has been found that, with the exception of certain specialized work, an engineer with a degree in any of the engineering sciences, who is aggressive, adaptable, and possessed of vision, will work into industrial research quite nicely." In another company the "chief petroleum engineer" is a mechanical engineer. A rubber manufacturer writes, "The limitation to mechanical engineers in your letter is difficult as the work of mechanical, electrical, chemical, etc., engineers is interlocked and interdependent." The vice president in charge of research of a large nonferrous metal industry writes: "To sum it up, it is difficult to say how much the mechanical engineer alone contributes to research in our own experience. I would rather say that he is an important partner, his importance being greater in the more strictly mechanical industries, and less in other industries." And the head of a governmental bureau says of an unusually comprehensive research program that "all of it is under the leadership and direction of engineers, physicists, and chemists, with no possibility of segregating them."

Where a distinction is made, opinions differ as to the importance of the work of the mechanical engineers. The director of one industrial research laboratory writes, "At the possible risk of offending the mechanical engineers, it is our opinion, based upon our own experience, as well as upon the contacts which we have had with other industries, that industrial research, or organized fact-finding of the more fundamental character in the field of mechanics, is carried out primarily by physicists rather than by mechanical engineers." But the director of the technical division of another company writes, "It would be proper to say that all of our research is in the field of mechanical engineering as you define it. The physicist and chemist that we employ assist in problems related to engineering." A research engineer in an aviation-engine factory writes, "Too much semifundamental work is laid out and attempted by physicists, chemical engineers, and chemists. In consequence, the application of their results is an attempt to apply the specific to the general without information sufficiently broad. In my opinion, work on engine principles should be conducted or directed by mechanical engineers"; and the director of still another industrial research laboratory writes, "Our feeling is that, as evidenced by our work for the past 10 years, the mechanical engineer at this laboratory will undertake any problem that comes to him, of whatever nature. My list indicates the wide variety that will turn up, running all the way from a new vehicle for the exploration of marsh territory otherwise impenetrable to the development of accurate instruments for investigating oil under conditions at the bottom of a well. In general, we will tackle any mechanical, electrical, or civil engineering problem that is handed to us and any similar problems that may be passed along to us by other groups, particularly the chemical group. The effect of machines is so great on the performance of fuels and lubricants that in all cases the mechanical engineer must have a hand in the design of the test apparatus, so as to standardize mechanical effects, before the chemist can determine anything much about the behavior of a lubricant as such, the mechanical effects being very much greater in magnitude than the total differences between lubricants."

These, and other statements in the letters received, emphasize strikingly the futility of attempting to classify industrial research workers according to the disciplines in which they were originally trained. There is far more difference between a research man, a production man, and a salesman than there is between a mechanical engineer, a chemical engineer, a physicist and a chemist. In Dr. Hirshfeld's words, "For real success (in industrial research) a very thorough grounding in many different and extensive fields of knowledge is required." Similarly an executive in a public utility writes, "Except as a narrow specialist, the mechanical engineer, like the electrical engineer, the physicist, the chemist, the metallurgist, loses his identity in organized research. Research is effective only to the extent that it brings to bear on its problems the help of all branches of science that may contribute." And an instrument maker writes: "Our field of work is so diversified, comprising measuring problems in electricity, magnetism, light, heat, radiant energy, sound and mechanical phenomena, that whether the engineer is nominally an electrical or a mechanical engineer, he becomes, after a training period, actually an applied physicist in a broad sense."

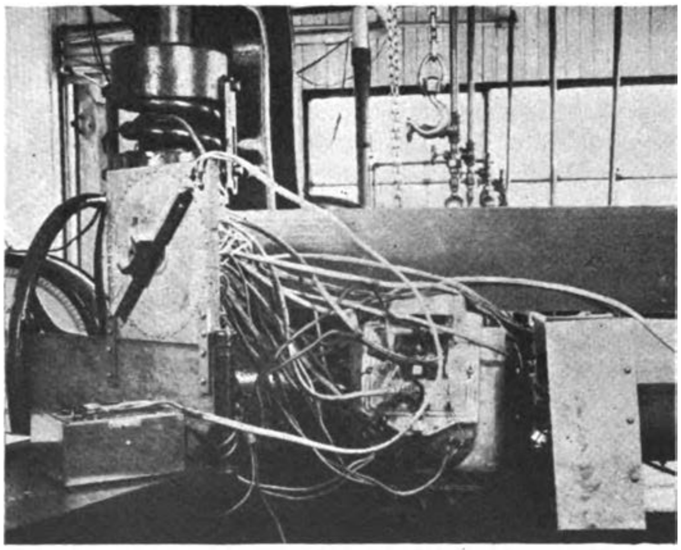

FIGURE 98.—Equipment for Investigation of Heat Distribution in a Conventional Railway Journal Box Assembly, Railway Service and Supply Corporation, Indianapolis, Indiana

No attempt will therefore be made to define a "mechanical engineer" for the purposes of this report. Anyone working in a field commonly thought of as within the wide range of mechanical-engineering activities deserves attention; so also does anyone who thinks of himself as a mechanical engineer but who works in some apparently remote and unrelated field, for these men may be showing the way to new research opportunities of great potential value to industry and of equally great interest to adventurous engineers looking for careers.

This uncritical attitude with respect to exact definitions is encouraged by a statement from a large automobile maker to the effect that "mechanical engineering enters into every phase of our work. It is necessary to have mechanical engineers in our metallurgy, physics, and chemistry departments, in addition to the straight mechanical engineering departments that handle problems in applied mechanics, engine development, and many related subjects."

Process Research

Since this report is concerned with industrial research, the major field of activity from which its material must necessarily be drawn is manufacturing or production, and it is no surprise to find more or less formally organized fact-finding permeating every phase of productive activity. To quote Dr. Hirshfeld again it is evident that "almost every department can profit from organized fact-finding studies."

A rough but useful classification of the various phases of production is one that distinguishes between process and product, and the material to be presented in the major part of this report will be arranged on the basis of this distinction.

Inspection of Raw Materials

One of the earliest forms in which what were often called "research laboratories" appeared in industry was a department set up for the testing of materials purchased for use in manufacture. Such procedures have been common in industry for many years, but it is customary nowadays to speak of them scornfully, if at all, in any report on "research." It is true that routine testing is very far indeed from research. Nevertheless, the inspection of raw materials should not be ignored in any attempt to describe comprehensively the research function in industry, for two reasons.

In the first place, groups strictly limited to raw-materials testing may, and often do, attack and solve problems of instrumentation and method and of "following up special tests under operating conditions" by means of what cannot but be regarded as industrial research. One industrial executive said, and many perhaps might have said: "I personally think the work our materials-testing group does is so high grade that it should be classified as research. The department concerned, however, questioned whether it should be so classified."

A second reason for mentioning materials testing in any survey of industrial research is that what starts as a routine testing laboratory so often develops later into a research department in the strictest and most useful sense. That this has been the normal thing in industry has been stated as follows by Dr. C. E. K. Mees: "The function of the research department has broadened very much in the last 25 years. Originally laboratories were introduced into industry to deal with the works processes, the control of raw materials, and the testing of the finished product. Then the laboratories began to develop new processes which could be applied in manufacturing. Then they began to produce entirely new products, until finally the research division of industry has taken for its province the whole technical future of the business and even of the industry as a whole."

Study of Raw Materials

One of the first of the additional functions which a routine materials-testing laboratory commonly assumes is that of studying the physical properties of the various raw materials available, both to insure wise choice among them and to determine their limitations for design. Often this leads to the use of materials new to the particular industrial organization concerned. Sometimes it leads to the development of wholly new materials or to wholly new uses of materials that have been developed for some quite different purpose.

This study of raw materials is one of the commonest research functions in industry. Perhaps half of those who have supplied material for this report have explicitly mentioned research on materials.

Thus a manufacturer of compressors writes: "In our standard designs we use valves of the poppet type of forged steel, or ring-plate valves of stainless or Swedish steel, or diaphragm valves of the flexing type using Swedish steel. Each of these materials must be evaluated, as well as its design limitations for application, in order to produce a satisfactory valve; and further, the metals and shapes of the seats on which the valves work, and the restraining medium to control their flexing or lift, must also be researched for design and application limitations."

Many other users of iron and steel report researches on those materials, such as "extensive research into the development of stabilized and other stainless steels, as well as assisting in development of satisfactory high chrome irons for use in corrosive conditions at high temperatures"; "research in high-temperature material" for steam- and mercury-turbine and exhaust-driven supercharger blades; investigations on the "creep and relaxation of turbine materials at elevated temperatures and the fatigue strength and internal damping of blade and rotor materials at room and high temperatures"; "analysis and survey of pipe characteristics for drilling wells of various types"; and many studies on such matters as "corrosion problems," which appear over and over again throughout industry, "methods of heat treating," "stresses in materials of engine construction," "radiography and creep testing," "best materials from the standpoint of machinability or plant production," "materials best suited (to our product) from the standpoint of life, economy, and performance," "the use of carbon-molybdenum steel plate for high-temperature pressure vessels," "the development and use of 70,000 p. s. i. tensile-strength carbon-steel plate for steam drums and pressure vessels," "permissible stress under conditions of plastic flow," and many other kindred subjects.

All this is, of course, research that is primarily metallurgical in nature; but in surprisingly many cases it is reported as done either by mechanical engineers and metallurgists working in collaboration or by mechanical engineers as such. Many industrial firms also report a growing research interest in plastics, a field where mechanical engineers are likewise apparently working in close collaboration with chemists.

Other studies of raw materials that have been reported deal with "the proper types of materials, such as

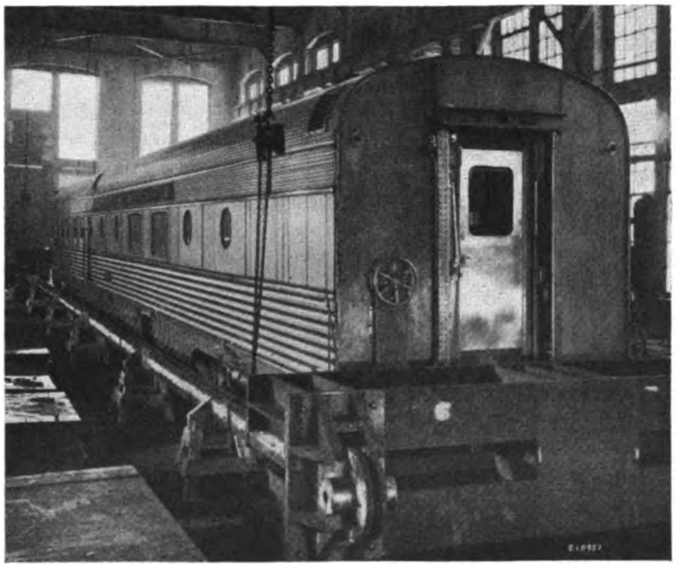

FIGURE 99.—"Squeeze" Test Machine for Subjecting Passenger Cars to Compression Load of 900,000 pounds, Pennsylvania Railroad Research Laboratories, Altoona, Pennsylvania

bronze, monel, stainless, etc.," for various types of oil filters, with "the selection of suitable materials, both ferrous and nonferrous," for railway signal systems by one firm and for piston rings another, with "the investigation of new materials for cylinders of internal-combustion engines," with "trying different materials, mainly for bearing qualities" for surveying instruments, with "the study of construction materials for oil refineries," with "a general study of pitting and galling of gear teeth," with "the rubbing qualities of various materials for labyrinth seals" in steam turbines, with "the flexibility and strength of control bellows," with "obtaining contact material which will stand up better under the make and break of current in voltage-control devices on automobile generators," with "better life of refractories" in cement kilns, with "the application and use of precious metals as linings for certain types of reaction vessel," and with "the development of suitable muds for oil-well drilling."

Instances of this sort could be multiplied almost indefinitely; indeed every factory has its raw-material problems and sooner or later brings a process of organized fact finding to bear on them. In activities of this sort, mechanical engineers are making one of their major contributions to industrial research.

Study of Manufacturing Equipment and Processes

From organized fact finding about materials to be used in manufacture, it is but a step to a similar study of the processes and machines used in the fabricating process. This constitutes perhaps the major field in industrial research today. It is a field in which mechanical engineers are likely to play a large part in every industry and a predominating part in many industries. It is the field in which mechanical engineers are making what is probably their greatest contribution to industrial research.

A classical example of industrial research of this type of the very highest quality and with the most far-reaching consequences is Frederick Winslow Taylor's work on the art of cutting metals and the closely related development and introduction of high-speed cutting tools by Taylor and White. The current phase of the long stream of research activity started by these pioneers is represented on the one hand by the Metals Cutting Handbook published by a research committee of The American Society of Mechanical Engineers in the fall of 1939 and on the other by a number of recent developments in hard-cemented-carbide cutting tools.

Many correspondents emphasize this function of the mechanical engineer in industrial research. One rubber manufacturer writes, "The mechanical engineer's function is to handle the physical design of the product and the manufacturing problems pertaining to it"; another in the same field assigns to mechanical engineers "the development of machines for new products and new ways of obtaining certain results"; a third writes, "Special machines for manufacture of product are designed and built to improve quality or reduce cost. Many of these are unique and hitherto unknown"; and a fourth is investigating "ventilation and air-conditioning problems," and the development of "apparatus to maintain uniformity of materials in process."

Two makers of power-plant equipment mention "the development of new fabricating methods, equipment, or procedure" and "investigations to determine labor-saving devices and reductions in manufacturing costs; also to solve difficulties in manufacturing and production."

One oil refinery writes: "Our mechanical engineers are concerned with evaluating the factors involved in heat transfer, temperature control, and agitation during processing as they affect the quality and nature of our products." Another writes, "While our research activities require chemical engineers to a greater degree than mechanical engineers, the latter are of considerable importance to us generally and indispensable in many cases. For example, in our processing we are continually improving both apparatus and process, and while we can purchase various units to be assembled, the coordination, the combinations, and particularly the instrumentation require systematic research." A third mentions a mechanical engineer who "is an expert on distillation. He carries out experimental work on distillation columns to determine the best type of packings, contact media, and mechanical design." And an oil-producing company mentions "investigations of control equipment for high-pressure wells."

An ordnance maker writes, "Our mechanical-engineering research program covers improvements to product and improvements to process" and continues, "Research work to improve processing includes the development of special machinery to reduce labor, increase output, and improve quality; also to consolidate two or more machine operations, to adapt new fabricating techniques to existing components and to redesign product where possible to take advantage of standardization of components, etc."

In a glass factory "an important part of the work of our mechanical engineers, independently and in collaboration with our other technical people, is connected with research in the improvement of glass making, especially with regard to new and improved mechanical equipment in the manufacture of glass."

From various manufacturers of optical goods came the following: "Considerable time is spent on processing as connected with design, mainly for the improvement of the product, but also for reduction of cost of manufacture"; "another function, which is probably the larger field, is the study of factory methods and processes and the design of new equipment based on the findings of these studies"; "the research activities of our mechanical-engineering staff include the development of new production equipment and methods and the design of original tools to improve quality, speed up production, and reduce manufacturing cost."

An excellent example of cooperative research on processes is the cottonseed research program, which was set up in 1932 "to study the mechanical problems involved in storing, conditioning, and cooking cottonseed," in the course of which it has been discovered "that cottonseed can be successfully cooked under pressure conditions at temperatures formerly thought destructive," with lowered costs, reduced losses, and greatly improved control. Progress is also reported on improving methods of separating the kernels of cottonseed without loss of absorbed oil in the hulls and of extracting the oil from the cottonseed meats with a minimum waste of oil left in the cake.

A locomotive builder "is devoting considerable attention to the development and extension of fusion welding, both in its application to locomotive construction and in other general fabrication work. In this connection recent extensive fatigue tests have been made to establish the value of fillet welds in locomotive tender tank construction."

A manufacturer of photographic materials lists eight "items of research work performed by mechanical engineers in [his] organization, either solely or with the collaboration of physicists or chemists," all of which concern process improvement, ranging from "investigation of heat transfer coefficients under conditions not usually encountered in industry," through "investigations of atmospheric impurities and means for their removal," to "investigation and development of special methods of preventing and controlling fires, explosions, decompositions, etc."

Fundamental research in the chemical industries is, of course, primarily in the hands of chemists and chemical engineers, but here, as elsewhere, mechanical engineers play a large part in process improvement. Thus a pharmaceutical house reports "a great deal of work on the distillation of aqueous and alcoholic solutions at low temperatures," on "the properties of gelatin and the manufacturing of gelatin capsules," and on "stainless-steel welding and finishing applications as affecting pharmaceutical products" as done by mechanical engineers. One of the largest chemical organizations in the country reports that "the research functions performed by mechanical engineers in this company are for the two main purposes of developing useful design information for new equipment and processes and for use in improving yields and cutting costs on old ones," and lists some 25 specific problems "along strictly mechanical lines" in which their industrial research groups are interested. In another large chemical organization, a "division specializing in the production of fine organic chemicals and synthetic coating resins utilizes engineering research in the development of (1) special heating equipment for sensitive reactions, (2) highly specialized apparatus for catalytic reactions, (3) more effective devices for agitation, and (4) automatic process control." A third large chemical organization lists 10 "major types" of research items about evenly divided between process and product research, and adds: "From the above it is evident that the mechanical engineers in our organization are engaged in research in many of the fundamental branches of mechanical engineering. Production methods, machine design, handling of liquids and gases with special reference to heat transfer, and the cutting and shaping of metals are among the most important of these."

In the electrical manufacturing industries, mechanical engineers play an important part. One of the largest companies in this field "pioneered in the development of large electric furnaces for use in copper brazing parts for [its] own production," developed "several very ingenious balancing machines" which "have made possible the present day large steam turbine," and conducted "researches in welding [which] have led to the substitution of fabricated parts in the frames of larger motors," to name but three of many significant researches. Similar studies of the possibility of "substituting fabricated steel for castings, utilization of die castings, plastics, etc." are reported from a variety of other manufacturing establishments. Another electrical concern reports "a large amount of work to develop improved equipment for observations of the vibrations in large machines," work on "the determination of stress concentrations" by photoelastic methods, and work on "mechanical problems in building and operating transformers," again to name but three of many examples. One of the somewhat smaller companies writes: "Our mechanical engineering research activities are confined to developments incident to products we manufacture and to the solution of manufacturing problems, such as design of suitable automatic machinery which is not otherwise available for economic and accurate production of our products." And another smaller company has a mechanical engineering group "which designs equipment for the manufacture of radio receiving tubes" and another which "designs equipment for the manufacture of incandescent and fluorescent lamps."

Important as are the process researches of mechanical engineers in all these various industries, it is probably in the metal industries, particularly iron and steel, that engineers are most indispensable in laying the foundations for, and carrying through improvements in, manufacturing methods.

In the nonferrous field one company reports: "Mechanical engineers in our various fabricating plants, working in conjunction with our central engineering department, research laboratories, and metallurgists, are always striving to improve the fabrication process. This work continually involves the design of new improved equipment, such as rolling mills, remelting and heat-treating furnaces, ingot-pouring equipment, leveling or flattening machines, forging, casting, and extrusion equipment, and handling devices for use with this equipment"; and, according to another firm making die-castings "further development and expansion of the die-casting process is dependent largely upon research of mechanical engineering, directed toward the improvement of dies, machinery, and equipment."

A chief metallurgical engineer in a large steel company writes: "The mechanical engineer undoubtedly has a definite place in research conducted by the steel industry, but he is seldom classified as a research worker. His work is usually practical research with a view of improving processes, production of a superior product, and economies of operation, and the importance of his work is recognized by all." Another large steel company reports research work handled by mechanical engineers on "the investigation and development of mechanical manufacturing devices," on "the investigation of ways and means for eliminating the cause of mechanical defects in products," and on "special problems involving heat transfer, air conditioning, etc., in conjunction with combustion engineers."

A steel-fabricating plant writes, "We have a mechanical and metallurgical research department which is concerned with the development of equipment, processes, technique, new materials, etc., for welding, hot working of metals and the fabrication of pipe, pressure vessels and other equipment." Another fabricating plant reports research by mechanical engineers with respect to "improvement in pipe mill processes and equipment, looking to reduced cost and product quality," and, in particular, with respect to "mass production of precision pipe threads." A third fabricating organization assigns mechanical engineers to fact-finding work "particularly with respect to can making and can sealing machinery," and lists 8 or 10 "typical problems now under investigation," such as "determination of the fabricating factors influencing the strength of soldered side seams, both from the standpoint of the mechanics of the can body and the application of solder thereto," "development of a satisfactory method for the high-speed soldering of black iron cans," and "elimination of solder particles and dust from the inside of the can."

These examples, and many others that could be cited, show the great diversity of the industries, and the wide variety of the problems, with respect to which mechanical engineers are performing useful and important research services by studying and perfecting manufacturing equipment and processes.

Control of Production

Like the inspection of raw material coming into the manufacturing plant, the inspection of parts in process, the control of the process, and the inspection and test of the finished product embody much that is routine and far removed from research. However, these functions often provide useful operating data and several companies that have contributed to this report have shown convincingly that the research method and approach have been used to great advantage in their inspection or quality control procedure.

One large chemical manufacturer reports that one of its divisions uses engineering research to advantage in the "development of automatic process controls." Similarly a soap manufacturer places responsibility upon the engineering staff for "control of process variables" and a petroleum refiner states that systematic research is required in order "to coordinate and combine successfully the instrumentation required in process control." A lubricant manufacturer requires a high degree of research skill in the development of new or improved physical testing equipment for controlling the quality and uniformity of his product. Two tire fabricators devote much research effort to the techniques of product testing, and one has developed an elaborate method for continuous testing with recording machines to control the accuracy of the tests. A clay-product producer has developed by reasearch, "laboratory and plant control equipment which has eliminated the uncertainty of the human element, making it possible to scientifically control the quality of our product." In the same general way a cordage mill and a maker of dental supplies regard the development of inspection and test methods as important research functions, and a manufacturer of machine tools, small tools, and gages uses "mechanical engineers in research work connected with following the product during its manufacture, and ascertaining, in cooperation with the inspectors, that it functions as planned."

The search for better instrumentation for routine inspection work has ramifications that can lead far afield from inspection routine. In this category belongs the research that led to such fundamental standards as Johansson gage blocks, and to all the secondary gages that have made mass production possible. Here also belongs the research that has led to the many ingenious automatic inspection devices and machines to be found in mass-production plants. Examples are machines that automatically sort finished pieces according to fine gradations of size within the established manufacturing tolerances, machines that automatically reject defective pieces, machines that sort pieces according to color, machines that continuously measure and control the thickness of the product of a continuous paper mill, inspection devices that permit the rapid inspection of the form of screw threads, or "the testing and charting of the accuracy of the involute curve of gear teeth," or "the lead of helical gears," and devices of extraordinary sensitiveness for the rapid inspection of surface finishes. Here also belongs the research that has led to the many available counting devices both of the scale and of the electron-tube types.

Finally, in this category belongs a deal of research on the problem of sampling, ranging from the elementary heaping and quartering technique for coal sampling that every engineering student knows, to some of the most obtruse statistical theory yet developed, the latter being the contribution of a well-known industrial laboratory.

It would be a serious error to assume that the field of routine inspection is one that does not, at times, give rise to important and profitable research, even in the narrowest and most limited sense of that word.

Management

To many it may seem strange to find a section on management in a report on the research activities of mechanical engineers. Since, therefore, some sort of a preface to such a section is obviously desirable, the following remarks of the late Dr. C. F. Hirshfeld are offered as a sort of text:

> When I was a student my dean stressed the fact that he regarded an engineer as a technically trained businessman. As I have grown older, and I hope wiser, I have appreciated more and more the significance of that statement. It is true that we have a place, and a large place for what I call technicians, men whose skill is limited to the application of technical knowledge to the technical solution of technical problems. But I think it is equally true that we have a scarcity of engineers in the sense in which my wise old dean conceived them. We do not have nearly enough men who have combined a technical training with an inborn or an acquired business sense and with business knowledge. It is only in the hands of such individuals that industrial research may be expected to reach the real heights of accomplishment . . . Much more profit may at times be obtained from organized fact finding in the so-called nontechnical or business departments than from technical improvement.

Even if this be granted, some will still argue that management research belongs to the social sciences rather than to engineering. But does this not imply an unduly limited view of what constitutes engineering? Engineering has been defined as the art of mobilizing materials, money, and men for the accomplishment of projects beneficial to mankind. Why should materials research alone be considered to the exclusion of research on the mobilization of money and of men?

Furthermore, it should be remembered that modern management, in the sense of an activity that can be rationally discussed and philosophized about, grew out of the thinking of engineers. Taylor, Gantt, Gilbreth, and most, if not all, of the other pioneers in this field, were engineers. And most of today's consultants in this field not only were trained as engineers, but carry that designation on their current letterheads.

That management should be regarded as belonging to the field of mechanical, rather than some other branch of engineering, is perhaps more debatable. But it may be remembered that management, in the sense in which it is here thought of, is an aspect of production or manufacturing, and that production is more akin to mechanical than to most other branches of engineering. It is commonly a mechanical engineer who feels most at home in a machine shop or a factory. By the same token, The American Society of Mechanical Engineers alone among the major engineering societies has an active professional division interested in management.

Finally, an examination of the discussion that follows will disclose specific activities, here classed as management activities, that not only lie definitely in the mechanical engineering field, but are of such a nature as to require experience in that field for their successful prosecution.

The work commonly called plant engineering, like other sorts of work already discussed, has its routine side, particularly in maintenance. But even here there is much chance for the research spirit in the choice of materials and methods. An example is whether to use brushes or spray guns in maintenance painting in a given plant under given labor conditions. Power-plant operation in a manufacturing plant also demands fact finding in the shape of operating statistics, fuel studies, load studies, and the like, that are well above the level of routine. Decisions on all such matters are commonly made by the plant engineer, usually a mechanical engineer. Indeed, to be a top-notch plant engineer requires a keen fact-finding instinct and an unusually wide range of knowledge and experience.

Similar problems are met by, and similar initiative is required of, specialists in building management in metropolitan centers. Such men are often mechanical engineers.

Plant lay-out, and particularly the routing and handling of material in a plant, also require organized fact finding and independent thinking, and this is a function commonly performed by mechanical engineers. It is specifically mentioned by informants as diverse as a manufacturer of roller chains, a manufacturer of lead pencils, a manufacturer of men's shirts, and a manufacturer of soap. Two oil companies mention the lay-out and development of pipe-line projects which are, in a sense, plant lay-out jobs, as the work of mechanical engineers.

Safety is an important aspect of plant management. One large research laboratory writes: "Safety is a matter of prime concern under the general jurisdiction of mechanical engineers. It involves statistical analysis, detailed study of specific machines and apparatus, and continuous inspection of conditions. The effort by our mechanical engineers to increase safety in our plants as well as safety of users of our products involves research in its broadest sense." Several other informants mention safety work, either in general or in the form of dust control. Two managers of engineering and inspection departments of insurance companies report extensive programs for promoting safety in the plants of their clients. One writes: "By correlation of industrial injuries, our mechanical guard-design unit develops new safeguards for the point of operation of industrial machines, either as a secondary protective device or for installation upon the machine at the time of original manufacture."

Time and motion study is mentioned by a number of companies, ranging from steel foundries to silk mills, and three informants mention the determination of costs as a research function of their mechanical engineers. One correspondent, a sales engineer, writes: "In the organizations with which I have been connected, it has looked to me as though the subject of cost analysis should be a regular engineering function rather than a clerical function." A large electrical manufacturing concern is regularly recruiting mechanical engineering seniors for its accounting and commercial departments, as well as for its technical work.

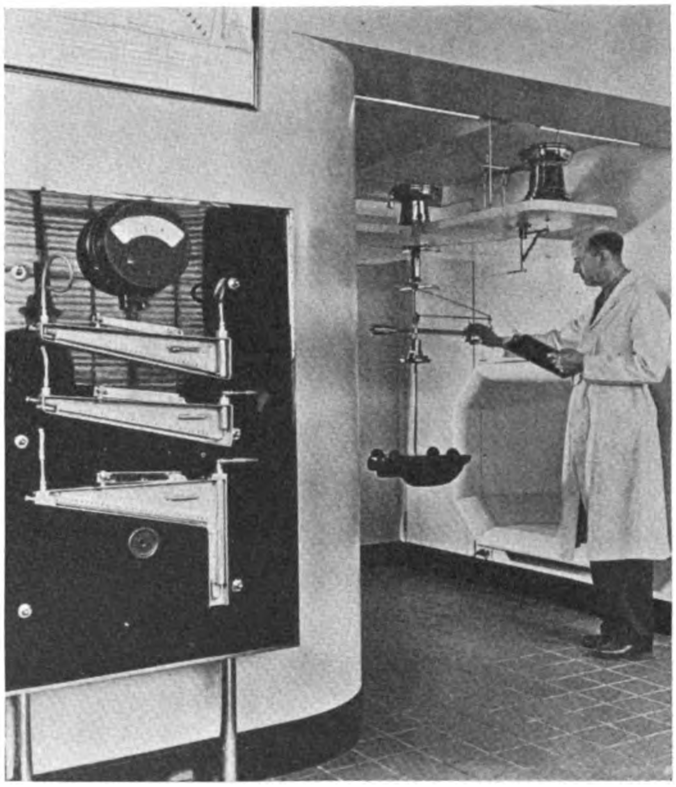

FIGURE 100.—Wind Tunnel Apparatus, Aerodynamics Laboratory, Chrysler Corporation Detroit, Michigan

All this may be summed up in two sentences from the admirable report prepared by the Detroit Edison Company for the Joint Patent Inquiry, which show the persisting influence of the late Dr. Hirshfeld in his own company.

> Under a policy of more than 20 years' standing, research investigations are not necessarily confined to engineering problems. The scientific process is equally applicable to other fields, and has been successfully applied in this company by the research department to the fields of purchasing, accounting, personnel, sales, and particularly to standardization in all branches of the company's activities.

Product Research

Product Development

Every manufacturing plant provides for testing its finished product either by sampling or, in the case of larger units, by block or other tests. Some of this work is pure routine; some of it is indistinguishable in method and spirit from inspection of work in progress, which has already been discussed. But often either the product or the circumstances are such as to make this product testing real research.

A striking example is the acceptance test of a large unit such as a boiler or steam-driven turbogenerator, particularly if it is of a new design or size. Often facilities are not available for thoroughly testing such a unit until it has been installed in its final location in a customer's plant, and the elaborate tests which are then made on it by the manufacturer and the customer in collaboration constitute real research on the part of both. To the former these tests yield confirmation of theory and of assumed design constants and data on which all further advances in his art will in part rest. To the customer such tests give the data which he will use in planning the operation of his whole power system under all the varying loads that it will have to carry. In such a case product testing is fact-finding research of the highest order.

More often the research aspect of product testing consists of performance or endurance tests of selected samples undertaken to check materials, design, or fabrication with a view to future improvement of the product. There are many examples of this sort of thing in the letters on which this report is based. A steel-tube manufacturer defines it as, "special testing to develop more complete knowledge of characteristics of established standard products," and an optical company as "the study of the performance of our product with the goal in mind of using the results of such research in supervising the redesign of the product." As an example of it, a maker of agricultural machinery reports: "Before any new machines (are released) or alterations are placed on existing machines they are first sent to what we term our dynamometer department (where each machine undergoes) a very thorough test to determine whether it has sufficient strength and whether shaft bearings and shafts have sufficient capacity for the work they are to perform." Another writes, "Research on all phases of track-type tractor and road-machinery design and performance (looks) toward constructions that will reflect more effective utilization of materials, increased life and versatility of machines, reduction of the physical effort necessary for operation, and greatly improved performance." A manufacturer of railroad cars reports: "We have conducted a considerable amount of test work on our car structures in order to check analysis, and connections, deflections, and similar features. There have also been compression tests made on our car structures to loadings approximating 1 million pounds compression." A roller-bearing maker writes: "Many of our investigations deal with fatigue and we have a large laboratory for the testing of full-size members in fatigue . . . Theoretical as well as practical results are being derived from such fatigue tests. An example of practical results obtained is the revision of axle-design standards of the Association of American Railroads." A maker of vacuum cleaners reports: "The cleaner research laboratory evaluates performance of complete machines as to efficiency and human-energy expenditure, carpet structures, and general problems of carpet wear and care; the parts test laboratory determines the operating life of elements, combinations, and complete structures under controlled conditions of temperature, humidity, light and oxygen exposure." And another firm reports: "Life tests under varying conditions, strength tests etc." of the parts of the delicate precision measuring instruments that are their product.

It is perhaps in the automobile, auto accessory, and internal-combustion engine fields that performance and endurance testing of both standard and new designs are most highly developed, and so familiar that none of the many reported instances need be quoted here. Furthermore automobile builders have developed to a fine art what can be called field testing of their product, as have oil-well-equipment makers, oil refiners, locomotive builders, makers of agricultural machinery, and many others. One correspondent remarks: "I wonder if we are not too inclined to label as fundamental research (only) that work which is carried on in the laboratory. When the laboratory worker removes his white smock and goes into the field and changes his micrometer caliper for a yardstick, most people are inclined to think that the fundamental nature of his work has changed, even though he is just as truly searching for new facts and new ways to put established facts to work." Many examples of field testing could be cited if space permitted, including the practice of many companies of installing the first example of a new model or design in their own shop or power plant for regular service under observation.

Only slightly different from field testing of samples of one's product is "accumulating and correlating field data regarding the behavior in practice of our rolling mills and auxiliary machinery, from the standpoint of power requirements, capacities, and durability"; or the rule of a maker of hydraulic turbines that "tests conducted in the (model testing) laboratory be checked in the field as far as possible"; or the considerable field research by a loom manufacturer, "to determine the causes for troubles which appear in the field" which was made the basis of a complete redesign of their standard loom; or the practice of a ball- and roller-bearing maker, which has in its laboratory "what we consider an important division known as the returned goods department, from which data is obtained as to the cause of failures in the field."

Are Design and Development Research?

The preceding section of this report inevitably brings up the question of the distinction, if any, to be made between ordinary design, development engineering, and research. Those who have responded to the inquiry for data vary greatly in their unconscious or conscious reaction to this problem of definition. One man writes, "The term research is applied to our laboratory for reasons which are largely commercial." A great many report without hesitation, as a part, or all, of their research activities, work done in "laboratories devoted to the design and development" of their products. Others say explicitly, "Research and development are conducted as joint activities." And some mention among their research facilities an "experimental department" which designs and builds new experimental machines and improvements on existing machines.

Many correspondents explicitly state their uncertainty as between research and design. Thus: "The distinction between research and engineering design is not plainly marked. Much original data must be obtained before a successful design can be made and the designation as research is therefore appropriate"; "Much of the work done in our technical division interlocks between design and research"; "The functions of the (engineering and research) departments often overlap, and no sharp line can be drawn between them"; "In solving these problems, it has been found expedient to combine the work of research and development"; and "Our entire engineering organization constitutes a research group working all the time toward these objectives of better products at a more economical price."

And some hesitate to call anything research. Thus one chief engineer writes: "Whether the (development) work outlined in the above paragraph would come under the classification of research is a matter of opinion. We do not classify any of our experimental work as such, but undoubtedly some of it is purely research"; and another says, "We believe that we would be rated more as a fact finding or experimental laboratory than a research laboratory in the pure sense of the word," thus modestly declining to accept Dr. Hirshfield's broad definition of industrial research. This is the more remarkable in that this same man goes on to say, "As differentiated from design engineers, we have mechanical engineers in our laboratory who follow the general principle of making critical experiments with simple apparatus to prove a principle before this principle is applied to the finished design. In most cases a single principle of a multiple operation machine will be explored, and when established, tests will proceed to the next principle. The results of these experiments are all assembled in a final design and the apparatus is sent to the laboratory for testing and revision." Many would feel that no better description of the spirit and method of industrial research could be asked for.

An interesting comment comes from the assistant director of research of an aircraft company: "At the outset it must be understood that the nature of research differs widely in different fields. In the aeronautical field the majority of work which we normally define as 'design work,' and not as 'research' would be considered as 'research' in many other industries. This is because the design of aircraft and their engines makes constant use of new materials, methods, and processes, so that the designing engineer is unable to refer to hand books and much of the time cannot refer to standardized practice. We do not consider the work of such men as research although it might reasonably be regarded as such."

And finally the vice president of a large metals industry company defines "The ideal (research) laboratory" as consisting of four divisions: (1) a fundamental research division working "without relation to any specific problem," (2) a division working "on special specific problems of the particular industry which have a sales value," (3) a liaison and development division, the duties of which are to act as a contact between (1), (2), and production, and to have charge of all experimental installations which put into effect the ideas developed by (1) and (2), after which they should be turned over to the production departments, which should not be expected to do the development work, and (4) a control-of-process and trouble-shooting department.

There is no question but that, under Dr. Hirshfeld's definition of research as being "in spite of all the mystery that has been thrown about it in recent years, . . . nothing more nor less than an organized effort to determine facts," a large proportion of the development work in industry, and a certain proportion of normal design work, deserves to be rated as industrial research.

New Products

The invention, development, and commercial launching of new products is what is commonly regarded as the major objective of industrial research, and practically every large, live industrial concern devotes a considerable amount of effort and money to this phase of its research program. Reports that have come in to the effect that such research is being seriously undertaken by industry are too numerous even to summarize in this report. An adequate picture can be obtained only by the quantitative type of survey that is being undertaken by the National Research Council.

It might be well at this point to call attention to a vague but significant distinction between invention, in the popular sense of a radical departure from previously existing products or processes, and development of new products or processes that grow out of older ones. Invention, in this sense, is the romantic, spectacular side of new product research, but, commercially speaking, it is relatively unimportant either in volume or in financial return. The really remunerative new products are usually the result of patentable or other developments just ahead of the crest of current practice in well-established fields. Wholly new ideas, particularly those which lead to new industries, are few and far between, and a long, hard road commonly lies between conception and commercial success.

New product research and development is often carefully organized and systematized. Thus a manufacturer of agricultural machinery writes: "This company, in its work in product development and improvement, carries on a constant and continuing program of organized fact finding on which to build its program of development. This fact finding begins, necessarily, in the field with its customers to obtain from them the basic data regarding the requirements of machinery they would like to have. This information is then assembled from all parts of the country, correlated and compiled, and then placed before new product committees for individual machines. On these committees for each important list of machines, sit an engineer, a representative from the manufacturing department, and a sales representative. This basis of fact then becomes the determining factor in the decisions that are made by these committees regarding placing of new products in manufacture. After this step is taken, and decision is made to manufacture a new machine, the engineering department takes up the problem of designing the machine, and the selection of materials and parts so as to meet the requirements specified by the committee, including the price at which it must be sold."

Another manufacturer in the same industry writes:

> For example, 13 years ago we recognized the need for better equipment for the building of terraces and other earth structures designed to prevent the erosion of farm lands. We studied soil behavior and the fundamentals of moving soil in fields. This resulted in the development of machines with blades or moldboards of proper curvature to prevent adhesion of soil and to reduce power input. This work resulted in the production of a line of terracing equipment.

Similar instances could be given for almost any other industry of the way in which careful planning, amounting almost to a routine, underlies most of the new products research of today.

A few examples are given below of new products resulting from industrial research. These examples are selected from the dozens mentioned in letters received, to say nothing of hundreds or thousands that might have been mentioned if the letters of inquiry had stressed a desire for such information. Those quoted have been selected, not on the basis of relative merit or importance, but merely to show the range and variety of industries profiting by this kind of research.

Among the new products reported are: Special boiler furnaces for burning bagasse, wood chips, sawdust, waste liquor from refineries, and other refuse fuels; hydrogen-cooled high-speed electric generators and synchronous converters with low windage losses; many different experimental locomotives (20 by one firm) "most of them built in cooperation with various railroads interested in developing better motive power"; streamlined trains, unit-container freight cars, and other novel rolling stock; nonicing carburetors and wing deicers for aircraft; automatic oxyacetylene welding machines "designed to take the personal equation out of welding"; coated weld rod with satisfactory slag characteristics and physical properties; precision grinders with kerosene-lubricated spindles; diamond-dust-impregnated grinding and cutting-off wheels; meters and control equipment for various industrial processes, similar to those now standard for boiler furnaces; remote metering and control apparatus with a range of hundreds of miles; geophysical instruments of very high precision and sensitiveness for oil prospecting; deep oil-well equipment for drilling, directional drilling, surveying, sampling, and air-lift and mechanical pumping; new machines and processes for the paper-making industry; special handling equipment in connection with dehumidification in the manufacture of shoes; development of new services and the machinery required for those services "so as to bolster up the dwindling laundry volume (in 1930)"; and a new kind of pneumatic-tube system for handling books between the old and new buildings of the Library of Congress.

New Uses and New Markets

Even commoner than new-products research, and even more important from the commercial point of view, is the search for new uses and new markets for established products that is going on in nearly every industrial establishment in the country. To the extent that it is planned and organized, and particularly to the extent that it involves field investigation and development of techniques and processes, it well deserves to be regarded as industrial research of a high order. Much of this work is done in customers' plants rather than in headquarters laboratories, and out of it has emerged a rapidly growing consulting engineering service, called sales engineering, that is profoundly modifying both the technique of salesmanship and the former position and function of the independent consulting engineer. Occasionally the organized search for new uses and new markets develops into a careful long-range study of industrial and even economic, social, and political trends, thus contributing to that most important of all industrial functions, the work of the administrative or "high-command" phase of management.

Some illustrations of this type of research are as follows. A ball- and roller-bearing manufacturer writes: "Our engineering department is set up in several divisions which in combination cover the entire industrial, automotive, and aircraft fields. You can well imagine that where we are supplying bearings to every type of industry we have a wide variety of engineering activity, both in the way of recommending proper application of bearings as well as following up their performance." Another firm in the same field writes: "We have one group which devotes its time to a study of the application of bearings to many types of units in industry. In fact, wherever shafts rotate new bearing problems are presented, and these are studied by mechanical engineers who, as a rule, spend much of their research time in the plants of manufacturers using our products. The various details of the design of the bearing mounting and of the lubrication and use of the bearing are studied, and recommendations made not only as to bearings but as to the design of surrounding parts used therewith."

A metals producer writes: "Our mechanical engineers are continually working with the users of aluminum and its alloys in an effort to make better and more economical use of this material. Applications include transportation equipment, refrigerating, air-conditioning, and chemical- and food-processing equipment."

A rubber manufacturer maintains research groups covering "The application of rubber or rubber and steel to the automotive trade," and "new uses for latex products—examples: Cushions, thread, mattresses, springs," and says "the plastic field is expanding so fast that new uses are of almost daily development."

A maker of power-plant equipment writes, "Considerable time is devoted to furnishing consulting services to our customers who encounter problems with our products"; an oil company uses engineers in the field to give "engineering advice to users of petroleum products"; another uses mechanical engineers for "cooperating with designers, manufacturers, and operators of all types of mechanical equipment in connection with design problems, metallurgical problems, lubricating problems, corrosion problems, methods of applying lubricants, filtering and reconditioning of lubricants, as well as all phases of petroleum products used in industry as an ingredient in the manufacture of products for commerce—for instance, ink oils, rust preventives, paper sizing, leather oils, wood preservatives, rubber pigments, paint pigments, etc."

In the sales field, a manufacturer of abrasives has a sales-research engineer who investigates "sales-research-engineering questions by frequent visits into the field and into customers' plants"; a fabricator of iron and steel engineering specialties says that its engineering service department "was organized about eight years ago for the dual purpose of training our sales engineers and developing a fact-finding set-up concerning the various fields of application for our products"; and an oil company writes, "In our field work some two hundred mechanical engineers are employed in direct selling, whose duties are to cooperate with manufacturers of mechanical equipment, etc., wherein petroleum products play a part. Any and all problems that arise wherein the possibility of research and improvement may show promise are cleared through this office and our laboratories."

Finally a steel foundry writes that mechanical engineers are in charge of some of its market surveys; and an oil company uses "mechanical, chemical, and petroleum engineers practically interchangeably" in studying the "new equipment requirements of industry" by means of the "survey and analysis of trends in industry, such as advancement in metallurgy, new processes in industry, changes in code requirements, etc."

How much farther this customer-contact work will develop in the future in the way of studying the broader, long-range trends of industry, and how considerable a part engineers, and particularly mechanical engineers, working in management, will play in this development, remains to be seen. This is probably one of the most fruitful research opportunities for engineers.

Fundamental Research

The contributors to this report describe a considerable extent and variety of fundamental research in their organizations. By fundamental research is meant accumulating the scientific data and formulating the general principles underlying the design of one's product as contrasted with studying particular applications of such data and principles.

This is a somewhat broader definition than that of one correspondent who thinks of fundamental research "as a blanket investigation with the object of turning up whatever hidden facts may lie in the unexplored field," or, as Dr. Hirshfeld puts it, "scientific or pure research with no immediate, practical goal in sight." Fundamental research, even in this restricted sense, has been found to pay by some companies, particularly by the chemical and pharmaceutical industries, and by certain well-known electrical and communication companies. Dr. Hirshfeld's wise comment is:

> It is as yet too early to say that in all cases (industrial research) may be extended profitably into what we generally refer to as pure research. However, I am inclined to believe that this will be recognized as a fact in the years to come. It seems to me that the history of industrial research points inevitably in that direction.

For the purposes of this report, however, fundamental research is taken to include not only "scientific or pure research" in the sense indicatod, but also a large amount of collecting of data, of measuring the properties of materials, and of studying general rather than particular problems, such as surface finishes, corrosion, and heat-transfer, that build up the stored information on which later engineering development must depend. Of this sort of fundamental research industry does a great deal.

One phase of such activity is library research. Many industrial concerns maintain their own technical libraries, and so called "special librarians" form a recognized branch of the librarian's profession. Some concerns have specialists whose sole function is carrying through literature searches on demand. Many formally organize the routing of current technical magazines and reports through their research and engineering departments.

Turning to fundamental research itself, an interesting result of analyzing the letters received is the emergence of a considerable number of fundamental problems that are common to a variety of industries. It will be possible to mention only a few of them. Thus fundamental problems in stress analysis are being explored by builders of dirigibles, railway signals, steam and water turbines, firearms, pipe, shoe machinery, locomotives, railway cars, oil-pumping machinery, tin-can-making machinery, and many others. Heat transfer is reported to be the concern of boiler makers, refrigerator manufacturers, insulation manufacturers, chemical concerns, oil refiners, photographic-supply makers, and a host of others. Fluid flow is a fundamental problem for makers of air brakes, chemicals and fans, oil-well and pipe-line operators, and makers of soap, cotton-spinning machinery, shoe machinery, pumps, turbines, and many other products. Different aspects of the general problem of combustion affect boiler makers, Diesel-engine builders, gasoline-engine builders, oil refiners, coal miners, and a variety of accessory manufacturers. Lubrication and corrosion touch nearly every manufacturer. There are also many examples of narrower interests such as the effect of moisture on leather in shoe factories, and the creep problem in solder in tin-can factories. And all manufacturers of raw materials do extensive research to provide prospective users with fundamental data on the various properties of their materials.

A few letters report specific projects in vivid enough detail to be worth quoting. A manufacturer of textile machinery writes: "We have a group of ten men studying better means and methods for improving the drafting operation of fibers which means studies of speed, surface characteristics, densities, and other factors that affect the attenuation of fibers from the bulk form to the finished yarn." A manufacturer of cotton textiles reports comprehensive research programs to secure fundamental data showing the effect on various fabrics of temperatures from room to 600° F., of pressures from zero to 60,000 pounds per square inch, and of various amounts of moisture. A maker of household appliances writes that an "acoustical laboratory devotes itself to the measurement and analysis of noise and the development of means of suppression." A manufacturer of machine tools reports investigations to "cover such matters as fundamental studies of metal-cutting processes—to determine the action of metal-cutting tools in the removal of chips; the study of cutting forces, tool life, finish, etc. Also the study of stresses and deflections in machine-tool structures and component parts, and the development of new mechanisms and hydraulic and electric devices and circuits."

Many other specific examples of fundamental industrial research are to be found in the literature or are matters of common knowledge. Among them are many systematic studies of the thermal properties of a variety of working substances suitable for use in prime movers or refrigerating machines, particularly mercury, ammonia, ethyl-chloride, and a variety of special refrigerants known mostly by trade names. Many examples of fundamental research in industrial laboratories are to be found in the field of applied mechanics, ranging from studies of balancing and other vibration problems and of transients such as water hammer and phenomena in surge-tanks, to studies of the mechanics of transmitting, recording, and reproducing speech and of the very complicated phenomena of architectural acoustics. Much fundamental research has lately been concentrated on surface finishes, ranging from molecular theory of surfaces, to studies of methods of producing super-finishes, and studies of their effects on machine performance.

A very considerable amount of fundamental research is going on in universities and engineering schools that is inspired by and partly or wholly paid for by industry. Usually this begins as private research by some member of the teaching staff, to whom industry turns as his reputation becomes established, or for whom support is secured from industry through private approaches or through such intermediaries as the Engineering Foundation. Wind tunnels and towing tanks all over the country are notable examples of this sort of industrially supported research. So also are a number of well-known hydraulic laboratories. At one college, one finds a nationally known specialist on grinding, at another, one on lubrication, at another, one on the design and performance of gears, at another, one on surface finishes, and so on through a long list of widely varying specialties. If it were possible to assemble a complete account of all the industrially supported fundamental research that is going on in universities and engineering schools in this country, either under contracts entered into by the institution itself, or in connection with the private consulting practice of individual members of teaching staffs, the importance of this sort of activity in any survey of mechanical engineering research would be even more universally recognized than it is.

Any program of fundamental research should have as one of its most important functions a policy of dissemination and publication of the results obtained. It is, of course, of prime importance that the organization itself should understand and use the fundamental data and theory developed by research. One organization "coordinates its studies through committees so that findings in fundamental research are quickly brought to the attention of those who will ultimately use the new knowledge, at the same time providing a seminar in which theory can be tempered with practice." Publication of fundamental research results to the engineering profession is increasingly regarded as a responsibility of industry and time and effort are spent to make the results usable by the general public. Thus in a memorandum on mechanical research prepared by an electrical company there appears the following statement. This company "has made it a policy to publish new findings as soon as reasonable protection has been secured under the patent laws. A major part of our findings are not patentable, particularly in the field of pure research. This practice is beneficial to industry at large and is particularly helpful to those in educational work who are attempting to keep abreast of the times. It is felt that this policy promotes the understanding and use of our products, and gives us our proportionate share of the increased business."

Types of Research Organization in Manufacturing

Industrial research is conducted, according to the letters received, under a wide variety of organizational set-ups. In the simplest cases, common in small organizations, such research as is done is instigated and carried through by some of the same men who are doing the production work itself. In companies large enough to have a separately organized engineering department, research is often a function of that department. The next step is ordinarily the organization of a separate research department, often with materials testing and routine inspection as the backlog of its work.

In still larger companies one begins to find decentralization into more or less autonomous branch plants on a product or a geographical basis, or both. In such cases one often finds an engineering department associated with each branch performing research along with other functions for the particular product or area involved. In still larger decentralized organizations, there will be a separate research department as well as an engineering department for each branch.

The next step in complexity of research organization is the establishment of a central research laboratory to supplement and unify the work of the separate branch engineering or research departments. In such cases there usually is, at least on paper, a definite basis for an appropriate division of labor between the central research laboratory and the branch laboratories or engineering departments. Either the central laboratory undertakes such work as is of interest to several or all of the producing branches, leaving to the branch laboratories the work germane only to their own branches; or the central laboratory undertakes the "fundamental" research, namely that not immediately applicable to some current production problem, leaving the "applied" or "practical" research to those more directly concerned.

Finally there is often some delegation of research activity outside the industrial organization altogether. This may take the form of joint or cooperative research by a group of organizations within an industry, through an association or institute. In such a case the association or institute is likely to concentrate on research intended to improve the competitive position of the industry as a whole against other industries, though some fundamental research of interest to the industry as a whole may also be undertaken.

Another form of delegated research, now becoming more common than formerly, is that undertaken by an independent research institute, such as the Mellon Institute in Pittsburgh which has served as a model for several others, or by a university or college, under a contract of some sort with an industrial client who bears a large part or all of the research expense.

An admirable example of cooperative delegated research was the Steam Research Program sponsored and directed by a special research committee of The American Society of Mechanical Engineers, financed by a considerable number of industrial firms, and carried on at two universities and at the National Bureau of Standards, which has led to three international steam conferences, to an internationally agreed-upon "skeleton steam table," to revised and much more reliable working steam tables in three different countries, and to greatly reduced uncertainties whenever the performance of steam-driven machinery is discussed across international boundaries.

Other examples with which the authors happen to be familiar are: An extensive program of research on the art of cutting metals recently concluded, one on so-called caustic embrittlement in boilers and on other aspects of feed-water composition and treatment, one on the characteristics and operation of super-pressure boilers, one on fatigue and one on creep of metals, and one on various aspects of the fluid-meter problem. Still other examples of admirable cooperative delegated industrial research can be found in the records of the Engineering Foundation and of several of the major national engineering societies.

Research in Operation-Type Industries

Because their product differs from that of manufacturing industries with a corresponding difference in organization, it is necessary to give different treatment in this report to the public utilities, electric, gas, railroad, telephone, and telegraph. In these industries, as in manufacturing, research permeates every phase of operation, though in varying degrees of formal organization, and the mechanical engineering-research responsibilities are substantial.

In describing the research functions performed by mechanical engineers in the public utilities, it is necessary to modify somewhat the classification used for the manufacturing industries. In the paragraphs that follow all the utilities will be discussed together under the following headings: Materials, operation, new devices and apparatus, and management and promotion.

Materials

Among the critical problems of the electrical industry the fuel problem looms largest because fuel is the largest single item of material cost in the generation of electricity. The sampling and testing of incoming shipments of coal borders on the routine, but the interpretation of the results and their transfer into generating-station-operation procedures involves a high degree of skill in research. Efforts to reduce air pollution involve research problems not only in the choice of fuels, but also in the design of combustion apparatus, and devices for the removal of impurities in the stack gases. Other materials problems, quite common throughout the steam-generating electric industry, depending also on the metallurgist and the chemist, include improved condenser-tube materials, low priced noncorrosive metals, a low priced noninflammable lubricant, etc.

In the gas and railroad industries, the testing of materials has the same important place, coal being the principal material as in the steam-generating electrical industry.

One of the telegraph companies reports that among the research functions performed by mechanical engineers in the organization is an "investigation of materials for use in telegraph lines and equipment, including timbers, metals, paper, insulating and magnetic materials, weatherproofing, and other finishes, etc."

The materials problem can best be summed up in the words of one of the electric utilities as follows: "Scientists create new materials and engineers make use of them but, somewhere between the scientists and the engineers, a great deal of work must be done to reduce the new material to something that can be reproduced with consistent known properties having value suitable for the engineers' calculations. Furthermore, it is necessary that some form of test be devised that will enable engineers to be sure that the material measures up to the standards. Many research-department problems arise from such necessities, particularly the problem of developing accelerated aging techniques that will give in a short time some measure of the long-time performance."

Operation

The spectacular research problems in the electrical industry are frequently those concerned with causes of operating difficulties. The reason of this is the size of the units involved and the large savings to be made by removing the difficulties. Furthermore, because the facilities for test under operating conditions are generally not available in the plant of the manufacturer, the utility is frequently called upon to cooperate with the manufacturer by providing space, steam, some labor, and sometimes research skill. The most interesting recent example of this is the construction by a manufacturer and installation in a utility plant of a 10,000-kilowatt turbogenerator with optical means for investigation of blade vibration, a phenomenon which has caused operating failures of impulse blading in superposed turbines operating at elevated temperatures and pressures. A second interesting example is reported as a "field investigation and research carried on jointly by manufacturer and purchaser on large boiler equipment, to determine actual in relation to theoretical circulation, slag characteristics, heat input rates, etc. It would be impractical for the manufacturer to erect and test boilers in his shops; therefore, tests and investigations must be carried on in the purchaser's plant and with his cooperation." Another utility reports research with the manufacturer into the causes for the unsatisfactory functioning of pulverized-coal burners. Many other examples have been reported showing the large measure of cooperation between the equipment supplier and the public-utility operator.

In the same way, the number and diversity of the causes of operating difficulties sought out by the operator alone is very impressive. A few are fatigue failure of high-pressure fan blades, turbine-foundation vibration, mechanism of failure of boiler tubes, reverse flow in condenser tubes, the elimination of arching in coal down-takes, the elimination of caustic embrittlement, the elimination of slagging in boiler furnaces, and the determination of magnitude of vibration and exact location of unbalance in rotating equipment. An impressive bit of instrumentation, reported by one operator, is "the adoption and development of the wet and dry magnetic methods of testing ferrous turbine blades to eliminate cracked and defective blades and the resulting development of jigs and measuring devices to accurately determine the root clearances of turbine blades for replacements, to assist in setting up the desired specifications of root clearances for safe turbine operation."

In the gas industry the problem of determining the causes of operating difficulties has the same general character, a few technical problems mentioned by correspondents being the fatigue failure of metals, pipe-joint troubles, pipe coatings, and corrosion.

In the railroad industry, the operating difficulties that are being subjected to active current research seem to concern lubrication, boiler safety devices, and air-conditioning of passenger cars.

New Devices and Apparatus

Another group of interesting problems comes to light under the heading of new devices and apparatus. Here the research problems deal with fact finding to define the conditions the new devices or apparatus are to meet, the decision as to the suitability of commercial apparatus, and fact finding leading to the design, construction, and test of the new equipment.

Examples that have been reported under this heading by the electric utilities are numerous and only a few will be listed to demonstrate the research quality of the problem. They include a new development in gas scrubbers for stoker-fired boilers, new apparatus for concentrating and dewatering fine solid matter in order that it may be handled with commercial apparatus without creating a nuisance when being handled through the city streets, development of a muffler for noise generated in electric substations by rotating electrical machinery and carried to the surrounding neighborhood by air-intake and discharge ducts, the development of high-pressure commercial steam-generating units, and high-temperature superheaters, finding suitable filtering materials for removing oil from the compressed air to pneumatic-control apparatus, and a temperature-compensated gas meter.

As the gas industry is a bit more stabilized, new devices and apparatus for operation do not appear as frequently, but reports were received of research in new test equipment.

It is with real regret that we are unable to include the complete statement prepared by the telephone industry of problems concerning new devices and apparatus in the mechanical field, that was presented at the request of the writers of this report. Merely naming some of these problems will, however, convey some impression of the high quality of scientific work done.

1. Increasing the intelligibility and naturalness of transmission of the human voice by telephone instruments through research by mechanical impedance measurements, as well as by other means.
2. Development of the crossbar switch for closing independently any one of 200 sets of contacts, the important magnetically operated element in the most recent form of dial switching equipment.
3. High-speed motion camera to take 4,000 pictures per second.
4. Design of the gothic U-type relay which depended on sound mechanical engineering in two factors, first, design of contact springs, requiring an elaborate extension of the classical beam theory; second, reduction of vibration manifested as "contact chatter."
5. Protection of equipment to resist earthquake shock.
6. Development of portable engine-driven generators for power supply in event of fire, flood, and the like.
7. Determination of satisfactory tension loadings of filaments of cathode tubes to prevent creep or stretching.
8. Development of optical measuring equipment for fragile grids in vacuum tubes for three megacycle coaxial cables.
9. Development of synthetic sapphire bushing for nonlubricated bearing in external anode water-cooled tubes.
10. Development of light, strong, hand tool for rolling sleeve on line wire.
11. Development of technique of pressure testing of nitrogen-filled cables.
12. Development of strand dynamometer for use in connection with placing of aerial telephone cables.

Management

Whatever its size and whatever its field no public utility can operate at full capacity 24 hours a day 7 days a week, but it must nevertheless be always ready to meet any demand that may be put upon it. In an electric utility this means generating capacity; in the gas industry it means storage; on a railroad it means a sufficient reserve of freight cars and of motive power; on a telephone system it means the right number of operators. In all cases there is need for planning based on a high quality of fact finding.

Making the most effective and economical use of existing equipment under various loads also requires fact finding and interpretation of a high order. An electric utility has to solve such problems as balancing each encountered load between its steam and water-power stations and between its base load, ordinary operating, and stand-by generating stations in the most desirable way; making effective use of existing or possible tie-ins with neighboring systems to increase use factors and standby capacity; increasing its own use factor by diversification of power sales and by sales research with respect to new services and new uses; working out mutually profitable arrangements with large, and, it is to be hoped, ultimately with small customers, with respect to byproduct power, process steam, byproduct fuels, and the like; and reducing the commercial cost of handling small customers.

In the gas industry, where industrial customers are relatively even more important, sales research plays a very large part in maintaining and increasing the prosperity of an operating company, and many important devices, lying definitely in the mechanical engineering field, have been developed for customer use by research engineers in gas companies. Also each operating unit of the gas industry has an important research problem in determining its own policy with respect to domestic heating.

The operating problems of a great railroad system range from load assignments for every type of locomotive over each division of the system, through the establishment of intricate systems for keeping track of and allocating rolling stock of all kinds, to the extensive study of rival means of transportation and customers' needs and desires as a basis for competing for his transportation dollar.

A telegraph or telephone company has, among other things to think systematically about, a complicated and important personnel problem.

All of these are management problems deserving of, and often subjected to, industrial research of the highest order. To the extent that engineers, and particularly mechanical engineers, are more and more tending to dominate the field of management, these may all be claimed as appropriate opportunities for the application of the research skill of mechanical engineers.

Conclusions

1. Many correspondents emphasize the difficulty of attempting to classify industrial research activities according to the particular engineering or other disciplines within which they fall, or according to the particular academic training of those engaged in them.

2. While testing of raw materials, of work in process, or of finished product involves activities that are usually of a routine rather than a research nature, a considerable amount of true research is often found associated with or inspired by these inspectional activities.

3. Research with respect to the materials, equipment, methods, and processes of manufacture is one of the commonest and most important types of activity of mechanical engineers in industrial research today.

4. Development of better products and of new products is a second very important type of research. On it all progress in the essentially mechanical industries depends.

5. Opinions differ widely as to where, if anywhere, a line should be drawn between normal engineering design, engineering development work, and research. It is the opinion of the writers of this report that research activities and the research spirit and technique should be broadly, rather than narrowly, conceived.

6. Research, and particularly field-research, for new uses and new markets for old products is of the greatest importance.

7. Fundamental research, broadly defined as including data gathering as well as investigations of a more purely theoretical nature, is very common in industry, and is very often an activity of mechanical engineers.

8. Research in universities and engineering schools which is partly or wholly paid for by individual industrial clients or cooperating industrial groups constitutes an important part of the great volume of industrial research.

9. Management can well be thought of as a branch of mechanical engineering. It is certainly a type of work in which a great many mechanical engineers are engaged. It is a field in which much is being done that well deserves to be called research. It is a field in which much more organized research should be undertaken by industry.

10. The formal organization of a company's research activities varies widely as between companies of different sizes and amounts of experience in research, but not in any significant way as between different industries as such.

11. While the activities of public utilities seem to differ in kind from those of factories, the differences are probably more apparent than real, and the research activities of utilities are as diverse and important as are those of manufacturing establishments. Research in management is probably relatively better developed among public utilities than in industry generally.

12. The writers of this report suggest for the consideration of those interested in industrial research the thesis that everything that anybody in industry does in the course of his daily work is either routine or research. It is suggested that the universal acceptance of this thesis as a matter of definition would do much to clarify the thinking of industry with respect to the fundamental basis of its present prosperity and future security.

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SECTION VI

9. THE SIGNIFICANCE OF INDUSTRIAL RESEARCH IN BORDER-LINE FIELDS

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ABSTRACT

The significance of research and development along the frontiers of industrial research represented by the border lines between sciences is considered. An account is given of some recent industrial developments in biochemistry, biophysics, geology, geochemistry, geophysics, rheology, and mineralogy. Consideration is given to the place of these border-line sciences in the modern industrial picture and to the educational facilities available for workers who may contemplate entering them.

Introduction

The history of scientific research demonstrates very clearly that, in popular scientific usage, the term "border-line research" has been widely taken to signify, in fact "embryo scientific field." In every epoch there has been a considerable number of real and exceptionally able pioneers who have undertaken the large task of training themselves in the region of the borderland between two sciences, so that that gap might be healed over, usually long after the structures on both sides had been solidly formed. It took great ability and great courage for men to do this. As in any other field of pioneering, exceptionally broad ability, flexibility of outlook, and the capability of uniting effort under conditions often confusing and discouraging, were required.

American scientific thought of today surely is based on broader concepts than ever before. Concomitant with this condition, the status of the border-line science worker among the majority of his fellows has been radically altered. Within so short a period as the last 10 years, the methods of work of the border-line scientist have received recognition to a very marked degree.

The extraordinarily rapid development of the conventional sciences in recent years has resulted in their approach on many fronts, and has created a large number of new border lines which hitherto went unsuspected. This fact, and its general recognition, are gradually bringing pressure to bear on our educational system to design standardized courses that will aid the border-line men in acquiring the training which they so sorely need. Research in border lines has already attained considerable recognition, and its position will unquestionably become additionally secure with the passage of time.

Work in border-line sciences, however, is rapidly increasing in difficulty as investigation of the more superficial fields is completed. Individual men are being called upon to possess a more and more extensive and specialized knowledge of each of the fields in which they have chosen to work. The ideal worker in a given border line should possess as extensive experience and information in each of the sciences which his work touches as the most specialized workers in those pure fields. The human limitation for the individual, except for the very rare and outstanding genius of universal capabilities, is very obvious.

The evident, though as yet scarcely explored, solution, is the very closely integrated border line group, made up of highly trained specialists in each of the sciences along the edges of which the group plans to work, who, while thoroughly and possibly somewhat myopically competent in knowledge of their fields, are yet so closely knit to one another that the organization as a whole functions as a unit, as a superorganism, as it were, with powers far greater than would be the sum of those of its individual components. The formation and operation of such groups require special conditions and the task is not easy—the very hardest part, like that of building a ship, being the attainment of the condition in which each component of the structure ceases to be an individual unit and becomes a part of the whole. Difficult though it may be, this development represents one of the most important modern trends in scientific research. Attempts to achieve the ideal condition are being made in several parts of the United States and abroad, with varying, but on the whole encouraging, success.

As always in our modern social structure, the tendencies that have become so markedly evident in pure scientific research have been closely paralleled in research in industry. Industries which are primarily dependent upon research in border-line fields, or which make large use of such research, have appeared in very considerable numbers over the past 20 years. The group method of research has received a very considerable portion of its impetus from industrial effort, for the technique is as applicable there as anywhere else. We shall be concerned in this section with this service of research in border-line fields to industrial enterprise.

In defining the scope and extent of border-line research, especially in its industrial application, it is necessary to set fairly arbitrary limits. As has been indicated, a discipline which was considered as a border line in one generation will be considered as an established field in the next. Thus, the border-line science of biochemistry is in the transition stage between its classification as a border line and its recognition as a full discipline. It is just at the peak of the active and highly productive stage which usually marks this transition. It has journals and texts of its own, but it still lacks the status of physical chemistry. Biophysics is in a less developed phase, where it may definitely be classed as a border line. There are still relativly few really competently trained workers in the field, there is no adequate journal, there are few good textbooks, yet work in that discipline is of the very highest importance.

Geochemistry and geophysics, because of their relative youth and the restricted practical applications which have so far been made of them, except of geophysics in mining and metallurgical spheres, are today to be definitely regarded as among the younger, border line sciences.

If for the frame of reference in which judgment as to the character of a discipline is made, its industrial application is taken, several other fields, not ordinarily considered border line in character, should be included. If we include in our definition of border-line disciplines not only those which overlap the sciences in their treatment of subject material, but those which are today in the pioneering stage of industrial application, we cannot ignore the special sciences of geology with its subscience mineralogy, and of rheology. Mineralogy has hardly budded from geology as a special science, and it is today one of the frontier disciplines from the standpoint of its application to a well-defined class of industries. Rheology, the science of the study of plastic flow, is a recent arrival from the domain of physics. Recently, in the United States, it has achieved the dignity of a journal of its own, and it includes a sufficient number among its professional disciples to warrant the maintenance of a national society. It is the handmaiden of a considerable range of industries, though its application there, as that of a consciously organized science, is of very recent date. It is especially helpful in the chemical industries, especially in that extremely important and still rapidly developing field of plastics.

Geology is one of the oldest of the sciences, and surely can present no claim to be of border-line character on the first definition. But upon the second, its claim is very real. Its first application to industry is not of very recent date, for a qualitative knowledge of geology has of course long been a part of the stock in trade of every mining engineer. The recent highly significant extensions of geological science and method, however, its inclusion within its operating resources of many novel techniques, and the expansion of its field of interests have in recent years very greatly changed the science as a whole and widened and radically modified its industrial applications. It should, therefore, quite definitely be included among the border lines of the second class.

The fields which have thus been selected as representative in the classes of border-line disciplines which we have defined include biochemistry, biophysics, geology, geochemistry, geophysics, and rheology. We may consider each of these very briefly to point out some of the more representative developments of the fields, and some of the more obvious opportunities which may await development in some of them and in the method of border-line research in general.

Biochemistry

The science of biochemistry in general is the servant of a very large number of industries, most of which, naturally enough, concern living matter in some form. Prominent among the commercial enterprises so served are the industries dealing with food packing and preservation, food production (the agricultural industries), biologically produced solvents, pharmaceuticals, leather, gums, resins, oils, fats, waxes, soaps, and other plant and animal byproducts, to mention only a representative few.

The science of the application of chemical methods to the preparation of foods found its beginnings in the days of Liebig. That of the disinfection and preservation of food materials and the manufacture of products by controlled fermentation, not to mention the entire recognition of biochemistry as a coherent discipline, is surely due to the genius of the immortal chemist-biologist Pasteur. If biochemistry thus originated in a reasonably remote period, its meteoric rise to the front rank of dynamic sciences has been a development of the last 30 years, and its widespread industrial application has come even more recently. Today, a large number of highly important industries are primarily dependent for their technological advance upon the science of biochemistry, and biochemistry serves a further considerable number in subsidiary fashion.

Typical of the more vital modern industries which are largely served technically by biochemistry are the entire food industry, pharmaceuticals, the agricultural industry with its many ramifications, those chemical industries which are particularly concerned with solvents derived from living organisms and other chemicals most efficiently biologically produced, the leather industry, and industries dealing with the production and preparation of natural gums, resins, waxes, and fats, and their intermediary or byproducts. These industries make up a block of commercial and technological activity which is of very great importance to the Nation as a whole, both in the relatively indispensable quality of the products manufactured and in the relative volume of commercial exchange involved.

The contributions of biochemistry to the food industry have been legion, but it will be worth while in passing to mention a few of the more striking and more recent ones, as typical of many more. The entire practice of food refrigeration, of great importance to national health and the foundation of a large industry, has been almost uniquely the product of the efforts of the biochemist, the biophysicist, and the mechanical and refrigeration engineer. To the biochemist has fallen the task of determining the optimum conditions of refrigeration for various edible commodities, and of investigating minutely the physical, but especially the chemical, changes that take place in food preservation. His has been the responsibility of studying the incidence and growth of molds and fungi under conditions of refrigeration, the changes of cell structure in refrigerated foods, the stability of vitamin content under these conditions, the action of natural enzymes at low temperatures, and the rates of gas exchange in refrigerated foods, to say nothing of that most difficult and important subject of investigation, the absorption of objectionable odors by refrigerated foods of delicate flavor. The work of the biochemist in food preservation has reached a climax of importance in two closely related fields. The first is that of the so-called "quick freezing" of foods—a process now of high importance. The great importance of flavor and texture in quick-frozen foods has necessitated an extremely careful study of the modification of cell structure under freezing, with a view to eliminating mechanical distortions of cell walls and destruction of cell products insofar as possible. It has also necessitated a much intensified investigation of the activity of enzymes in frozen food, with a view both of eliminating the harmful effects of autolysis on the one hand and of preserving insofar as possible the valuable properties of vitamins on the other. The second field where biochemical research in food preservation has been of particular value has involved the ripening and the preservation of fruit. Studies of the rate of respiration and other gas exchange in bananas have been important to the successful mass transportation of that fruit which now forms the basis of a major industry. Biochemical studies of the reaction of pigments in the fruit skin to ethylene compounds and other related chemicals have made possible the artificial ripening methods now such a boon to the citrus industry.

Studies of the processes of drying, lyeing, and sulfuring in fruit preservation have been of equal value, and their successful prosecution, very largely by biochemical methods, has made possible a considerable proportion of the American raisin, dried apricot, and prune industry. Hand in hand with this work has come the study of the biochemical action of preservatives, especially in the fruit-juice field, both upon the product and upon the consumer.

The biochemistry of enzyme changes in meats is quite as important as that of vegetable foods. The enzyme papain, and some of the other naturally occurring enzymes of fruits, notably of the pineapple, have been found to have a very marked action on meat products, and have now been commonly adapted for the "tenderization" of sausage coverings in that industry, with good success. The mechanism of the action is being studied further. It has been found that the color of beef, a very important quality in determining its marketability, bears a close relation to the biochemistry of the meat, and that, other things being equal, meat of a higher sugar content tends to be of a more brilliant red color.

The biochemistry of bacteria is an extremely important field for the food industry. On the one hand, knowledge of this kind permits closer and more intelligent control of noxious micro-organisms at every stage of food preparation and preservation. On the other—and almost equally important—it opens to industry the important fields of the cultivation of beneficial strains. The applications are multifarious. Bacterial reactions are at the base of very many activities, including manufacture of cheeses and alcoholic beverages among the consumables, the production of many commercial solvents and other chemicals, which at present are or may be synthesized by bacteria more economically than by any other means, and, not the least important, the preparation and preservation of farm stock feeds for the agricultural and agronomical industries. An important field has also developed rather recently about the use of bacteria, and especially of microfungi, directly as food. The high food value of the larger fungi, as exemplified in the mushrooms, has long been recognized. It has only been fairly recently, however, that the great value of some of the yeasts for direct consumption has attracted the attention which it deserves. This is a relatively virgin field which the work of the biochemist alone can be expected to expand.

The preparation of important chemical byproducts from vegetable sources is another very important biochemical field. We have briefly mentioned the extraction and study of plant enzymes which has fallen to the work of the biochemist. Equally important is the study of such fruit byproducts as pectin, obtained both from the larger fruits and, oddly, from fungi. The detection, extraction, and preparation of natural resins, gums, oils, fats, soaps, and waxes is an especially important biochemical procedure. Although the synthetic plastics industry has displaced the use of some natural gums and resins, there are very many which, either by virtue of natural superiority, susceptibility to economical production, or both, are destined to remain predominant for many years to come, if not permanently. The biochemistry of these products, of their production, and of the plant which produces them, are of the highest industrial importance. Chicle, the product of a tough-leaved bush of the tropics, lies at the base of the entire chewing-gum industry, and a suitable artificial substitute has not been found. Natural dammars and lacs are irreplaceable for many uses. The biochemistry of many of the plant oils, and particularly that of their successful hydrogenation and other chemical modification, has become of the very highest importance to the food industry. The hydrogenation of cottonseed oil has placed at our command a higher hydrogen-content natural oil, analogous in many ways to some of the animal fats, at a hitherto impossibly low cost. Further, the substances so prepared are in effect new, and totally unlike naturally occurring products in many of their properties.

Biochemistry is at least as essential to the pharmaceutical as it is to the food industry. The plant and animal vitamin industry exceeds $120,000,000 in its annual sales. Most of these vitamins are biochemically prepared from a great variety of sources, and are purified and finished for medical use. We have said a little of enzymes in their relation to the preparation of foods. As general biologics, a very large number of them are biochemically isolated from both plant and animal sources and are annually placed on the market. Rennin, invertase, papain, pancreatic extracts, pepsin, amylase, microbial proteases are all relatively commonplace today, and they find the greatest variety of uses. Perhaps the most important of these is still in medicine, but others are very nearly as conspicuous. Enzymes play an extremely important part in the tanning industry, while invertase is widely used in the hydrolysis of sugar sirups. Enzyme digestion of the gelatin base is an important step in the recovery of silver from photographic film, often a very economically important procedure to the cinema industry.

Quite as important as the vitamins and enzymes obtained from plants and plant products are some of the other substances biochemically produced from them. The chemistry of natural flavorings and perfumes is very important both in their production and for their successful imitation in the synthetic industry. The biochemistry of plant flower colorings is of interest to the synthetic dye industry. Important, especially in medicine, is the biochemistry of plant alkaloids. Quinine, caffeine, the cocaine derivatives, and many other plant alkaloids stand as examples of the work which biochemistry has done in this field.

The biochemistry of narcotics, sedatives, and anaesthetics began as an essentially nonindustrial study, devoted to the noncommercial alleviation of human suffering. The tremendous amount of information which it has accumulated, however, as to the action of special chemical groups in human anaesthesia and narcosis, as well as in germicidal and toxic action, has become an important base of the entire pharmaceutical industry. The knowledge gained in recent years has been so remarkably precise in nature that it is at present possible to build a compound biochemically to specification, so that it will be a narcotic, a sedative, an anaesthetic, or a toxic substance, or may combine any or all of these properties. No single field of biochemical work has been of higher medical value. Closely related to this field is that of chemotherapy, with its industrial production of germicidal agents, and of such justly famous substances as sulfanilimide and sulfathiazole. The preparation of vaccines and of other disease-preventing and immunization sera is a closely related activity and is one of the most difficult, as well as the most significant, fields of all biochemistry. Important too are the diagnostic agents which are being developed in the biochemical laboratories of pharmaceutical concerns.

The textile industry is by its very nature intimately dependent upon biochemistry. Studies of the biochemistry of silk, wool, and cotton have on the one hand vastly improved the qualities of these products over the last several years, and on the other have given great impetus to the production of synthetic materials. Recent biochemical studies of the structure of cellulose and lignin have been of interest for the production of artificial cellulose compounds of commercial importance, such as cellulose nitrate, cellulose acetate, and ethyl cellulose, on the one hand, and various products derived from lignin on the other.

The agricultural industries are effectively served by biochemical science. We have already considered the importance of biochemistry in the identification, isolation, and modification of plant and animal products. It is equally significant in the rearing and care of the productive organisms. The study of soils and of the composition and action of fertilizers has formed a very active part of biochemical activity over the past several years as have biochemical studies of bacterial nitrogen fixation, a process the understanding and abetting of which is so vitally important to the large-scale restoration of depleted soils through crop-rotation methods. Biochemical investigations of insecticides and fungicides are of great commercial and economic value, and are being undertaken in the laboratories of several of the larger chemical companies. An especially interesting and important modern feature of this investigation has been the development of substances toxic to invertebrate life, and therefore excellent insecticides or fungicides, and yet nontoxic to warm-blooded animals. Such insecticides may be sprayed upon crop plants until their maturity, and no labor is necessary in removing traces of the chemicals before processing. Many of these substances are themselves vegetable alkaloids, which were originally detected, extracted, and concentrated by biological means.

The production of solvents and other commodities of direct industrial utility by biological means is usually a process primarily involving bacteriological techniques, and therefore peculiarly well served by biochemistry at every step of the way. The most important of such commodities, of course, is alcohol, but others are continually coming to the fore.

The leather industry is one which is today considerably served by biochemical techniques. The processes of tanning have always been recognized as primarily biochemical, but it is only within comparatively recent years that effort has been made on a really serious scale to understand the methods involved or to improve them. Though one of the most ancient of arts, tanning until very recent years has been an almost entirely empirical process. The recent contributions of biochemistry, however, have been considerable. Controlled tanning through the quantitative use of enzymes is being studied extensively. The nature of the chemical changes which are undergone by leather in the course of the process are being thoroughly investigated, and many modifications have been introduced into the final product. The leather industry is one which, at the moment, does not face direct serious competition from any synthetic product of like properties, but, for very many purposes, it must resist the encroachments of artificial substitutes equally or nearly equally good. The flexible and semiflexible resins and modified rubber or rubber-containing products will serve many of the uses of leather. There are, however, still enough large-scale applications remaining in industry for which leather is uniquely suitable to justify very much further work on the biochemistry of the product and its preparation.

The leather industry has rather recently posed some extremely interesting problems in the biochemical field of bacterial disinfection. Many hides which are sent to tanneries, especially from the East, have been stripped from animals which have perished from anthrax, and the danger of the communication of the disease to tannery workers is very serious indeed. The problem of sterilizing such hides is an extremely important and difficult one. Heat sterilization is out of the question, as are most chemical treatments, because of the irreparable damage which they do to the quality of the hides. Much interesting work has been done with gaseous disinfectants, but the combined necessity of high toxicity, high penetrating power, and low injuriousness to the hides, the chemical composition of which rather closely approaches that of the organisms that are to be eradicated, makes of this one of the most interesting and industrially important of modern biochemical problems.

Though biochemistry is chronologically one of the older of the border-line fields, its industrial applications are very far from having reached a level of saturation. Opportunities too numerous to list individually are continually presented to biochemistry in the service of industry. The biochemistry of plant alkaloids is still in its relative infancy, both on the purely investigative and on the applicational sides. The chemistry of immunization reactions in the human body is of the highest importance for the preparation of suitable vaccines and toxin-antitoxins. The biochemistry of cancer is of course very little understood today, despite recent investigations into the rate and character of the metabolism of cancer cells and the various aberrant features of their metabolic mechanism. No problem could be a more important one for biochemistry, both from the standpoint of pure medicine and that of industrial disease.

There are very many plant products and byproducts which present most important economic implications for the future. The solution of the problems concerned in their extraction and their suitable marketing will be the task of biochemistry. New drying oils are needed for the paint and varnish industry. The range of plants that may directly supply these oils has been fairly well investigated for this hemisphere. The investigation has only been begun, however, among plants in the southern hemisphere, especially in the New World, and the most important things may remain to be discovered. It will be the task of the biochemist to devise the methods of assay which the botanist will apply in his search, to perfect methods of extraction and analysis of the oil. Even more important than this, however, because of the much wider field which it opens, is the biochemist's investigation of the natural drying oils known at present, with the view of artificially altering their structure and so introducing properties as new and as valuable as those of an entirely new product. Work of this kind constitutes a far wider sort of exploration. Its success has already been attested on numerous occasions, most dramatically, perhaps, through the various hydrogenation techniques.

The field of biochemistry is sufficiently well recognized, and has been established long enough for its educational facilities to be obtained readily. Biochemistry is recognized as a definite entity in the chemical departments of most of our outstanding universities, and a good share of educational time and talent is devoted to its better students. The principal improvement for which we can hope is that the educational facilities in the field may be broadened in geographic scope, so as to include a good many of our smaller institutions of learning from which they are now absent. The situation is far from being as satisfactory as this in the border-line field which we shall next consider.

Biophysics

The science of biophysics is designed to fill the same borderline position between the domain of physics and biology as is occupied by biochemistry between biology and chemistry. It is, however, a very much newer science than the latter, and much less completely recognized today. By the same token, its very best days lie all before it, and we are only beginning to conceive of its coming immense industrial importance. It is one of those border-line fields which is deserving of the most vigorous and active encouragement. For, just as chemistry as an industrial science is far more widely recognized today than physics in the same role, although physics is potentially quite as important, so the position in industry of the handmaiden of physics, biophysics, is not so clearly understood as is that of biochemistry. Biophysics is still in that stage where the industrial importance of certain special applications of the science is widely recognized and acknowledged, but only the veriest beginning has been made of linking these isolated bits, and the methods which achieved them, into a unified and coordinated discipline, backed by a suitable educational system and suitable professional recognition. All this must come in the future, but the sooner it can arrive, the sooner and the more will American industry profit.

It must suffice here to notice in passing some of those isolated and more striking examples of the industrial applications of biophysics, considering those as illustrative of the sort of service which would be performed over a much broader field by a unified discipline. We may then consider for a moment some of the steps which might profitably be taken in the direction of the establishment of such a discipline.

Biophysics is concerned with physical processes in living material, with the use of physical means in measuring biological reactions, and with the reactions of biological materials to physical agents. In consequence, its work falls roughly into two main divisions. The first deals with the reactions of living organisms to physical agents, such as heat, light, and the various radiations of longer or shorter wave length. The second is concerned with the accurate physical measurement of biological processes by means of instruments devised especially for the purpose and made possible through the discipline of biophysics. Both fields have extremely important industrial as well as medical applications. The two spheres cannot be entirely delimited artificially, so that it is inevitable that each field to be cited will, in many cases, share the characteristics of both.

Biophysicists have made a beginning in the study of the reactions of living organisms to electromagnetic radiations throughout the spectrum, and the applications which have already been made to medicine and to industry have been considerable. Since the work is, relatively speaking, only begun, the future seems most promising.

Biophysical investigations in the shorter wavelength radio region have resulted in the development of the "fever machine," and the development of the fever therapy methods in medicine. Other industrial applications have stemmed from the same method. Such is the use of short-wave radio fields in relation to the drying of oils, the condensations of resins, and other modifications in industrially important products. It has even been investigated in relation to the preparation of special types of food products, such as some of the dried cereals, and no one can tell what the future may bring in further applications of the method.

Biophysical investigations in the infrared region have resulted in the development of the infrared "translux" viewer, of special value in certain types of cancer diagnosis. Investigations of particular importance to the agricultural and agronomic industries have been made of the effect of infrared irradiation upon photosynthesis in green plants, and upon the rate of laying and rate of growth of birds in the poultry industry. A particularly interesting application of infrared spectroscopy has recently been made to important studies in photosynthesis, the infrared absorption spectrum of carbon dioxide being used as a delicate criterion of the rate of absorption of this gas by crop plants under various conditions of soil, moisture, and illumination. The study of soil heating in relation to root growth and crop production is also a most important one for the agricultural industry. Special infrared lamps have been developed to aid in the drying of natural oils in paints and varnishes.

Because of the relatively much longer time that the visible spectrum has been studied by man, and because of the relatively large number of measuring instruments that have been developed in this field, biophysical investigations in this region have been unusually profuse and of unusual significance.

Extensive studies have been made of the bactericidal action of light, and the results have been put to good practical use in industry and in medicine. Similarly, studies of the effects of light on the more important of the useful micro-organisms, notably on the butyric and lactic acid bacteria and the fungi involved in the making of cheese have had important repercussions on procedures in the dairy industry. Many more studies of this kind are badly needed, in view of the ever-increasing range of bacterial and fungus forms that are becoming of industrial significance.

The careful study of the effect of visible light of different wave lengths on photosynthesis has been of the very highest importance to agriculture. The investigation of the mechanism of photosynthesis, which is only in its infancy, has been primarily a biochemical matter, but the biophysicist has contributed the methodology for the direct investigation of plant growth in light of differing quality, and in differing total illuminations. The demonstration of the striking differences in the requirements of various crop plants has alone more than justified this work. The results have already led to marked modifications in commercial greenhouse technique, and may go much further. The dairy and poultry industries have likewise been much influenced by studies of the effects of quantity and quality of illumination upon the rate and total production of milk, egg, and meat products. Modifications of the first and second have been especially industrially important.

Biophysical studies in the region of the visible spectrum have been of consequence in quite another field, important to industrial medicine and to industry as a whole—the field of opthalmology, and the study of the effect of intensity and quality of light on the human eye. Studies in the relative sensitivity of the human retina to different portions of the visible spectrum have enabled progressive industrialists to provide the quality of shop and office illumination to promote the highest efficiency of work and the greatest happiness to workers. Physical studies in the production of suitable fluorescent light sources have aided this development enormously in the last several years. On the other hand, biophysical studies in the reaction of the human eye to various qualities and quantities of light have resulted in the development of methods of opthalmological diagnosis and treatment of very high value to industrial medicine.

When we enter the ultraviolet region, we first come to deal with radiations of sufficient quantum energies to produce fairly extensive ionization in the biological materials upon which they impinge, resulting in the production of numerous effects which yield much material of interest for the investigation of the biophysicist. The chemical changes which ultraviolet radiation may bring about have enabled biophysicists to be of great industrial service in devising means for the artificial irradiation of processed foods and of suitable sterols, with consequent vitamin production. The process has come to have fully as much industrial advertising as scientific value, and is in some danger of having its merits overstressed thereby, but there is no denying its wide applicability and industrial and medical import. Of similar importance have been biophysical studies of the effects of ultraviolet illumination on the human skin and eye, the production of erythema, and the synthesis of vitamins under these conditions of extreme significance to medicine and to industry.

The property of ultraviolet light of inducing fluorescence in various substances has led to important biophysical applications, both industrially and medically. In many cases living organisms fluoresce differently from their nonliving counterparts, and the property may be made of importance in a large-scale distinction between the two. Medically this has proved of importance in the examination of teeth. In industry, it can be put to analogous use.

Biophysicists have made extensive industrial use of the bactericidal properties of ultraviolet light. As a disinfecting agent, ultraviolet light is especially suitable in treating surfaces where no part is in shadow, because of the limited penetrating powers of light of this wave length. Special sterilizing lamps have been developed by industry which have proved especially useful in the disinfection of milk and water supplies, where it has been possible to flow the liquid past the light source in very thin sheets. The lamp has achieved a more limited application in the disinfection of refrigerators, and to a certain extent, in the treatment of fruits, where it has been desirable to produce sufficiently intense illumination to eliminate deep shadows. Lamps designed for the irradiation of patients or animals suffering from rickets can, by the use of suitable sources and filters, be converted into sterilizing agencies, thus making the tool one of unusual flexibility.

It has been claimed that the use of ultraviolet light may be efficacious in the treatment of certain types of surface cancers. This potentially important industrial-medical application must await further biophysical study. In photography, however, ultraviolet light sources are of the greatest value to the biophysical investigator, both because their fluorescence-inducing properties make them of great value in the fluorescence microscope, and because their high absorption in cellular nuclear material and this high resolving power make them of great use in cell photomicrography. The fluorescence microscope finds very considerable industrial application in the analysis of materials which are composed of an intimate mixture of substances, where it is desirable to estimate at a glance the relative composition. It is much used in the textile industry in this way. The absorption ultraviolet microscope finds its greatest use in medicine.

The very great industrial and medical importance of X-rays is well known. In this field perhaps more than any other, further investigations of the biophysicist are needed, on both the medical and the industrial sides. The subject of rontgenography, the taking and the interpretation of clinical X-ray photographs, has become a science within itself, of the very highest importance for industrial medicine. No tool is so useful as the X-ray tube in the diagnosis of industrial injuries, and none, perhaps, has been so rapidly or so markedly developed within recent years. In this work the biophysicist has had, and will continue to have, a controlling part, for no field demands a more intimate combination of physical, biological, and medical knowledge, and in no other field are the requirements in regard to the accuracy and the completeness of information in these various fields on the part of the worker more strict. Very recent developments, such as the modern extremely high voltage X-ray tube, various techniques of stereoscopic photography, and constantly changing techniques of interpretation of rontgenograms, are all indicative of the rapid development of the field and the activity of biophysical research in it.

The second great biological application of X-ray techniques, and perhaps the most widely known, is to cancer therapy. Here too the biophysicist is of prime importance in a subject very close indeed to industry. The requirements for the treatment of deep-seated tumors have given great stimulus to the development of the technique of producing high-voltage X-rays, and have influenced X-ray tube design as much as any other factor. Recently, the application of new types of high-voltage sources, such as the Van de Graaf generator, has brought about interesting advances. Much work has been done in the impregnation of tumors with the salts of elements of high absorbing power for X-rays, with the purpose of trapping as much energy as possible within the tumor mass.

Quite as important as the influence of biophysics on X-ray tube design has been its development of tools for measuring total applied X-ray dosage, upon which X-ray therapy has depended for its quantitative interpretation. Extensive researches in various forms of ionization chambers have evolved types which are compact, portable, easily used, and quite accurate as relative standards, and other, more bulky designs which yield accurate absolute measurements and serve as calibration standards. These designs have been taken over into industrial uses quite apart from the medical services which they were originally expected to perform.

A third application of biophysics in the field of X-rays, which gives interesting promise and is as yet in the very preliminary stages of its development, is the production of mutations in various crop plants of interest by irradiation of germ cells. It has been demonstrated that new forms of plant life can be produced in this fashion which will have the true characteristics of induced mutations. They will breed true to the new type for an indefinite number of generations after the irradiation has been performed, and in some cases the mutation may be such as to enhance the commercial value of the altered product. A thorough estimate of the commercial practicability of this procedure must be left to the biophysicist of the future.

Cathode rays have been used by the biophysicist in applications on the whole very similar to those of X-rays and ultraviolet. It has been found that cathode rays, like ultraviolet light, will increase the vitamin content of irradiated sterols, although the very limited penetrating power of the beam sets a definite limit to the industrial practicability of the method. Cathode rays, again like ultraviolet light, cause fluorescence in many materials, and this property finds industrial applicability. Mutations can also be produced under cathode irradiation. Finally, cathode rays have been shown to have definite therapeutic value in certain cases of skin cancer, where, because of the very high absorption of their energy over short distances, they may be of greater value than X-rays.

Newest of all the radiations to be considered as a practicably useful tool by the biophysicist is the neutron, and here the possibilities are almost unexplored and are highly exciting. Very little information has as yet been obtained of the therapeutic value of neutrons, but experiments of many types are very actively under way. A property of neutrons of great interest is their power of inducing artificial radioactivity in elements of importance to the physiologist. This quality has made possible the initiation of a wide program of biophysical experiments with the so-called tracer elements, in which the progress of the element through the human, animal, or plant body can be accurately traced and recorded with ionization counters, by virtue of the energy spontaneously released by the radioactive element. Researches of this sort are, of course, by no means confined to biological subjects, and may find important industrial applications, such as in the detection of minute traces of various impurities in metals, and the study of the rate of passage of substances through other substances. These developments have in turn initiated further intensive research in the perfection of the design of Geiger counters, to increase their sensitivity and their range, which in its turn may have important industrial repercussions. Finally, the use of neutrons in special types of rontgenography seems a definite possibility, and their properties in this connection may be destined to render them of considerable utility in biophysical research, as well as in biophysical industrial application.

These are but a few of the consequences for industry and for industrial medicine, cited merely as examples of the investigations of the biophysicist into the reaction of radiations and living things. The entire field is relatively new, and the number of workers therein is at present so meager as to imply that the most important results remain for future workers to produce. The encouragement of further research in such fields, and the provision of adequate facilities for training in it can hardly fail to yield large returns.

We may turn for a moment to the consideration of some of the more striking individual contributions, direct and indirect, which biophysics has made to industry. One of the greatest single contributions has been the development of extremely sensitive measuring devices for following reactions in processes involving plant or animal products and their adaptation to industry. Conspicuous among these have been potentiometric devices, "pH meters" developed for laboratory use and further adapted to large-scale industrial operation. Many products which are prepared on a large scale, notably in the food industry, change in conductivity during the operation, and specific conductivity can be used as a measure of the finishing of the product. For such operations physical devices which will give nearly continuous readings of specific conductivity are of immense value as indicators, and are widely used. An interesting application of this sort is to be found in the standard manufacture of tomato ketchup and of fruit juices in the food industry. Photoelectric devices play a very important part industrially in many of the biological industries whose activities include processes where colorimetric indicators are required. They are particularly widely used in the food industries in the standardizing of colored products, and in the textile manufactures. Spectrophotometric apparatus is a vital part of research, control, and production equipment in very many industries where color is an important characteristic of the goods manufactured. Densitometers find a somewhat similar use in the biological industries, being designed especially for the delicate measurement of quantities of light absorbed in different materials. An instrument of very recent design which is of particular use in the biological industries is the so-called "color analyzer," which is a special type of spectrophotometer designed to reproduce the absorption curve of colored substances throughout the visible spectrum.

Equipment for the observation of reactions at abnormally high and abnormally low pressures represents an important contribution of the physicist to the biological industries. Many important biological reactions, especially in the food industries, will readily take place at abnormal pressures which cannot be carried out under atmospheric conditions.

The technique of centrifuging and ultracentrifuging are nearly vital to the food and pharmaceutical industries, and equipment of this sort represents a very important contribution of biophysics on the side of instrumentation. Ordinary centrifuges find much use in processes of separation, precipitation of solid from liquid materials, and the breaking of emulsions. Ultracentrifuges find their principal biological use in the separation of sera, viruses, and hormones, and in the separation of various other mixtures of molecules of high molecular weight. Filtration equipment is equally important to the biological industries in the separation of particles of differing sizes of a somewhat larger size range. Recently the techniques of biophysics have supplied some new and radical filter designs of greatly improved utility, notably a filter manufactured from sections across bundles of tiny glass tubes cemented

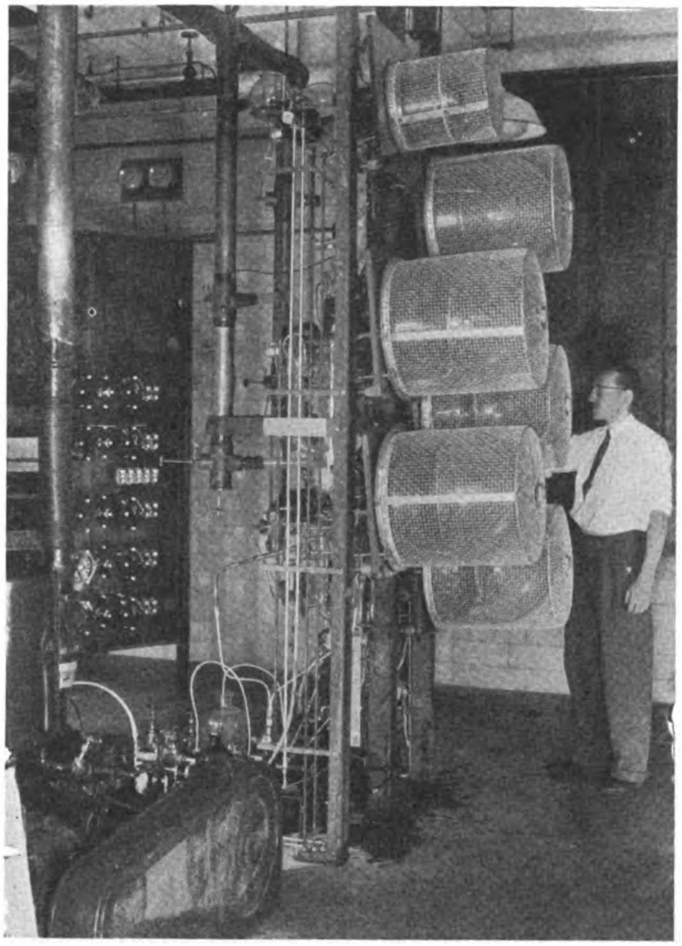

FIGURE 101.—Six-Plate Centrifugal Molecular Fractionating Still in Operation, Distillation Products, Incorporated, Rochester, New York. (Subsidiary of General Mills, Incorporated, and Eastman Kodak Company)

together, the bore of the tube being controlled and uniform, so that the "pore size" of the filter is predetermined. Techniques of pressure and vacuum filtration have been developed to a high degree in the biological industries. The application of supersonics to suspensions has been widely used in the biological industries as a means of promoting reactions, of settling suspensions, of breaking or forming emulsions, and, occasionally for the disinfection of such liquids as milk, since it has been shown that under certain conditions cavitation may be fatal to bacteria.

High-speed photography is of very considerable importance to a number of biological industries in the analysis of various unit operations in their processes and in the study of the fundamental physical properties of some of the substances they handle. As such, the method is used more nearly as an analytical than a routine tool.

There are a number of other physical tools which find wide, if scattered or occasional, use in the biological industries in special applications of analysis or process work. Such, for example, is the absorption electron microscope, for which uses are only beginning to be found, and the applications of which will probably widen rapidly in the coming years. Such too are the various designs of Geiger counter, the principal biological uses of which have centered about the application of tracer elements to the analysis of biological processes, already considered. Electrocautery instruments, and the fever-therapy equipment previously described find principally medical applications, although the latter may be of some use in the foods industries. And finally, electric soil-cable heating has important agricultural applications.

These are but a few of the many miscellaneous ways in which physics and biophysics serve industry. They have been selected almost at random, to give a sampling of the extent of that vast but new and very rapidly growing field in which the biophysicist of the future cannot but be of the very greatest industrial service.

Biophysics has been recognized as a science so very recently that adequate academic facilities for training in the field are still woefully lacking. The adequately equipped biophysicist must first of all be possessed of a sound working knowledge of experimental physics, and must have the "feel" for the handling and the application of physical tools. Adequate educational facilities for this side of his training are available in abundance in the ordinary good undergraduate and graduate courses in experimental physics in most of the universities of the country. Much more important even than this, however, the biophysicist must have an extremely good and comprehensive knowledge of biology. If he is in academic or theoretical work, he must be competent to choose for his experimental material biological organisms which will be preeminently suited to his needs. Superficially similar organisms differ so widely in this regard that a good choice of material may be one of the most important steps in assuring the success of an undertaking. In industry it is predominantly important that the biophysicist be widely familiar with the range of biological materials with which he will be required to deal, in order that his design and use of physical equipment shall be adapted in the best possible manner to the work in hand.

The educational facilities for posts of this sort, either in industrial work or in academic fields, are pitifully meager in this country. A very few universities have set up biophysical departments, and are attempting to design courses to meet a growing need, but in most cases students are obliged to select courses in two very different fields considerably at random, with no mature coordinator to help them solve a very difficult problem. The difficulty is increased for the student by the fact that it is only very recently that the two subjects have been related even in academic minds, so that he is virtually obliged, first of all, to discover for himself the intimate relations between the fields, and then to unearth courses which will make the details of these relationships clear to him—all at a period of extreme youth and with a very limited experience and perspective. This is an extremely difficult task but one whose successful solution is of very great future moment to a large division of industrial research. The designing and execution of courses in biophysics and the delineation of the work of the biophysicist as a recognized profession is one of the most important tasks facing the universities and industry in the immediate future.

Geology—Geochemistry—Geophysics

Geology, geochemistry, and geophysics are so very closely linked in both scientific and industrial practice, and particularly in the latter, that it has seemed best to treat their activities, and the work of the men in them who serve industry, as a single unit.

Geology is in its very essence a border-line discipline, both in its academic characteristics and in its industrial applications. From its very inception geology has been a composite science, consisting essentially of special applications of physics, chemistry, and biology. In undertaking to describe, and, insofar as possible, to explain the features of our nonliving environment it has had to include within itself, by definition, a very large range of subjects and fragments of subjects. This fact is reflected in the number of subsciences into which the discipline has been divided. Cosmic geology, geognosy, petrology, lithology, dynamical geology, structural geology, physiography, paleontology, stratigraphy, economic geology, mining geology, glaciology, oceanography, metamorphic geology, and mineralogy are all recognized as scientific entities.

The portions of geology, geochemistry, and geophysics which are of particular industrial service are those which relate especially to the fields of mining and metallurgy, petroleum production, the production of natural gases, soil study, geodesy, seismography, and water research. The last four of these fields of activity are more suited to governmental than to private enterprise, because of the bulk and expense of the research required, and the public-service nature of the results expected. They have, accordingly, been very largely shouldered by governmental agencies, and hence are not of primary concern here, vitally essential though they are to human welfare.

Of the several industrial activities of the United States which are primarily served by the border lines of geology, geochemistry, and geophysics, the two most important are certainly the mining and petroleum industries. The mines of the United States employ collectively over 1,100,000 workers of whom roughly 750,000 are employed in the production of coal, and another 200,000 in metal mines and metallurgical works. The United States is probably the world's largest producer of copper, iron, lead, and zinc, produces roughly 10 percent of the world's silver, and in 1934 produced 30 percent of the world's coal. Both in the mining of metals and in metallurgy, geology, geochemistry, and geophysics play predominantly important parts. The function of geology in facilitating the location of natural ores is as old as mining itself, but has recently been widely extended. Geochemistry plays an especially important role in preliminary ore analysis. Descriptive industrial geology as a field science contributes predominantly to the large-scale assaying of terrain in the prospecting of original mine sites, to the identification of ore-bearing strata once the mine is opened, and to the determination of the mechanics of the way in which those strata shall be exploited. Petrography and mineralogy are of especial importance in the prospecting of both mine sites and ores, and industrial workers trained in these fields find wide opportunities of work. The large-scale handling of ores, and the extractive and refining processes for their metals developed in connection with them, are peculiarly the province of mineralogy and especially of geochemistry. Modern methods of ore flotation, ore roasting, and other extractive processes bear witness to the contributions that have been made in this field. Recently, entirely new mining techniques have been required by the development of the important sources of radium in Canada. Some of these have been provided by the mining engineer, in the overcoming of the tremendous physical handicaps of mining in such cold and inaccessible regions. Others, however, necessitated by the peculiar nature of the chemical product, have been provided by men from the ranks of geochemistry and geophysics.

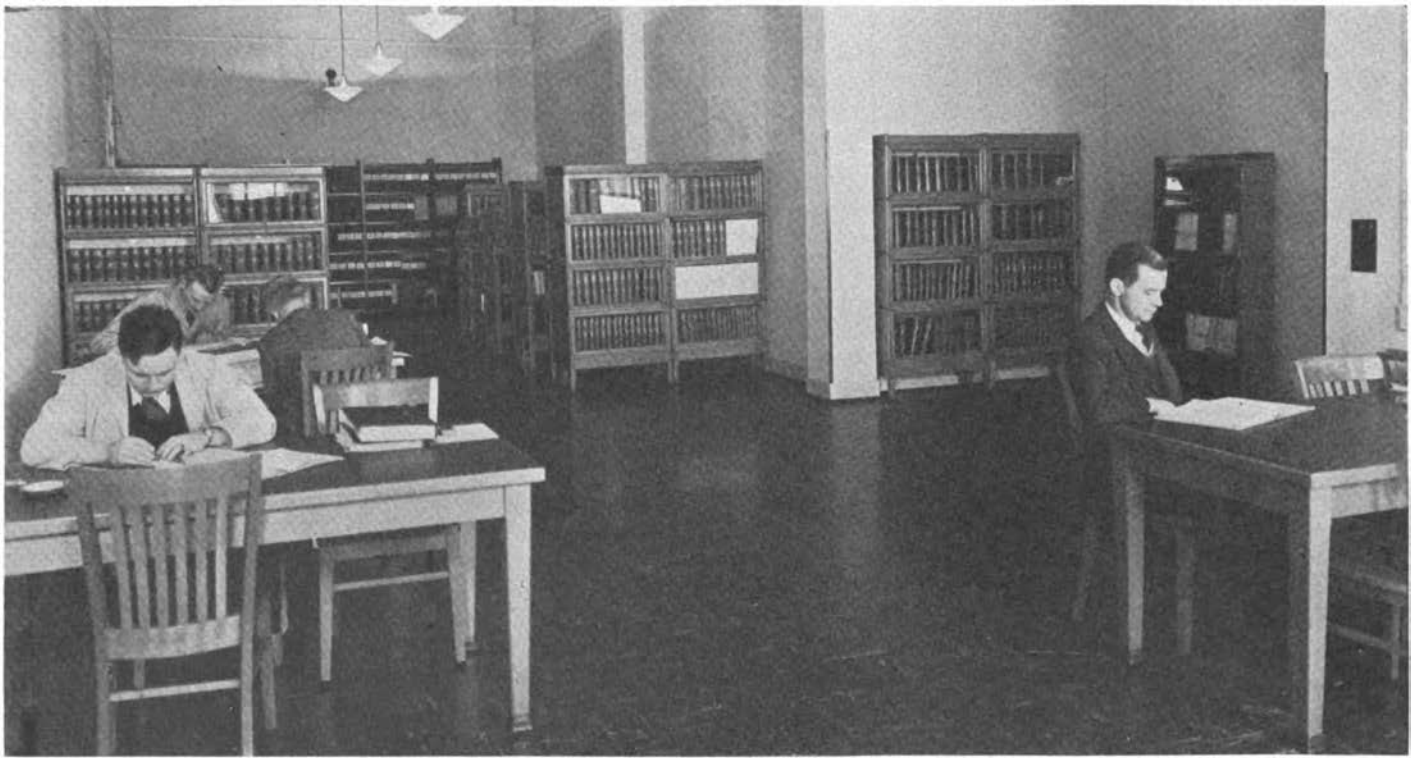

FIGURE 102.—Research Department Library, American Can Company, Maywood, Illinois

The researches of Hall in the aluminum-metallurgy field provide a classic and outstanding example of the titanic contributions that chemistry can bring to metallurgy and the mining industry. The magnetic prospecting for metallic ore deposits provide as great a tribute to the geophysicist in this field. The Frasch process for the extraction of sulfur provides an equally classic example of the work of the geophysicist in a nonmetallic mining field. The introduction of hot water through pipe drills to sulfur deposits to melt the sulfur, and the subsequent forcing in of air under pressure, and the literal blowing to the surface of 99 percent pure sulfur, the whole operation being conducted through a single set of three concentric pipes sunk at one drilling, has further advanced the whole sulfur-mining industry than a century of previous work.

The mining and processing of asbestos exemplifies to a high degree the contributions of geochemistry and geophysics to both the production and processing of a unique and valuable product. Asbestos varies in quality enormously with the nature of its deposits and to a certain extent with the method of its extraction. These differences are very largely related to the nature of the ores with which it is associated, and the methods for the essays of these ores have been almost entirely the work of the geologist and his physical and chemical congeners. The processing of the material is an even more critical business, and here the geochemist and the geophysicist, and especially the former, are all-important. Very recently the geochemist has been able to demonstrate that asbestos may be combined mechanically with certain other substances to yield a product having a whole new range of physical properties, unsuspected hitherto for asbestos, while none of its known valuable qualities are sacrificed. This opens up a very large, and entirely new field for the geochemist of the very greatest interest.

The petroleum and natural-gas industry is one which is especially indebted to the geophysicist on the prospecting and to the chemist on the refining and preparative sides. The geophysicist has completely revolutionized the once cumbersome technique of oil prospecting by his development of gravitational methods, described elsewhere in this report. The production of sturdy field equipment, for the simultaneous detection of both the vertical and horizontal components of the force of gravity, of sufficient delicacy to identify the presence of large masses of subterranean water or salt in the "salt domes," yet so rugged as to permit of its transport across country by truck and its continuous use at a field site, represents an important contribution to the advance of a major industry. Very recently the geophysicist has made another outstanding contribution to this field, unexpectedly enough by an application of the mass spectrograph, whose original designers surely had in mind for it applications far different from those of the petroleum industry. It has been found possible, by making very careful borings in an area suspected of containing petroleum and taking progressive gas samplings, to detect with the mass spectrograph the existence of heavy petroleum molecules in concentrations heretofore far too low for identification. By checking at intervals along the exploratory shaft, it is possible to identify increases in concentration of petroleum gases, with the consequent probability of the proximity of oil, with a rapidity and above all a delicacy which would have staggered the imagination of any petroleum industrialist but a very short time ago.

If the work of the geophysicist is all-important in the prospecting of petroleum, that of the chemist is equally so in the preparation of the product, once obtained. The complex maze of modern refining and fractionating processes, the entire science of cracking, the existence of the present range of special-purpose treated petroleum products, are all the work of the field chemist, aided by the pure petroleum chemist of the laboratory. To these two do we owe two things of tremendous importance in petroleum affairs—the enormous range of uses to which petroleum products can be put, and the great abundance of suitable petroleum cracking and fractionation products for the immense drain which their principal use as a fuel puts upon the existing natural supply. These are vital contributions indeed.

Not the least important field in which the geochemist and the geophysicist have worked has been that of coal mining, a field requiring wholly different techniques from those pertaining to any other extractive process. To a greater degree than elsewhere, perhaps, these have been contributed by the mining engineer. The identification of coal strata, however, has been very considerably the task of the geologist, and research in the preparation of the product has fallen predominantly on the shoulders of the geochemist and geophysicist. We owe to them the present range of uses of coal and coal products.

The study of soils and of the processes of erosion is peculiar to geology and to geochemistry and geophysics. Like seismography, water research, weather study, and geodesy, it tends at once to require research on so large a scale, and its results tend to be of such general national value that it properly belongs rather to the field of national than of industrial research. However, its results are of such interest to agricultural industry that it surely merits passing notice in a treatment of this kind. The study of the physical characters of the soil, all-important to agriculture, is the work of the geophysicist. It has been carried forward in the last years in the United States and in the Union of Soviet Socialist Republics to a greater extent than anywhere else in the world. The study of the nutritive content of soils is a primary concern of the geochemist, and very much work has been done here. The study of soil erosion is of such oustanding national import, and has been so highly publicized in recent years that further mention need not be made of it.

Rheology

Rheology, the science of flow, is so closely associated in its work with the sciences of mechanics and of physical chemistry that it has only fairly recently been distinguished from them as a separate discipline. It is very probable that the force which brought about this distinction was the unusual industrial applicability of the techniques of the science. Fairly recently the science of rheology has acquired an American journal devoted to its work and the status of an essentially separate science.

Since rheology is primarily concerned with the process and mechanics of flow in gaseous, liquid, and solid substances, there are very few industrial processes to which the properties of materials are of predominant importance which do not employ it. It is important in studies of the rates of flow, the viscosity, the turbulence of flow of gases in heating plants and in industries manufacturing gaseous products. It is highly important to the aeronautical industry, for studies of the rheological characteristics of air are of extreme interest to the aeronautical engineer. Studies of processes of liquid flow are indispensable to the chemical engineer, who may have to deal with liquid flow on a plant scale. Studies of flow in both liquids and solids are vital to such chemical enterprises as the plastics industry, where the control of major processes depends upon frequent accurate determinations of viscosity in the liquid phase, and the rate of flow or deformation in the solid condition. The question is of equal importance to the glass industry, to many food industries, and indeed to any industrial process where the physical state of the product must be altered during preparation. Determinations of viscosity constitute one of the most delicate and reliable indicators of the progress of a chemical reaction, and one of the most outstanding processing characteristics of many valuable chemical products. Rheology is also the handmaiden of many of the engineering sciences, being notably useful to engineers engaged in road building, in the engineering of waterways, and, through its contributions to the study of photoelasticity, in structural engineering. Wherever the flow of liquids or the deformation of solids must be adequately determined, dependence is placed upon the rheologist.

Rheology is a border-line science in the sense that it depends upon specialized branches of physics and physical chemistry. It has essentially taken these over unchanged, however, and merely combined them for use. In this sense, it is less specifically a border-line field, and more nearly represents a combination of two already highly developed branches of science. For this reason, the student desiring to enter rheology as a profession possesses rather good educational advantages. His field will not require so broad or general an education as is demanded by some, and he will be able to adopt the educational facilities already available. The design of specialized rheological courses in the universities, however, has none the less lagged considerably behind the need for them, and the initiation of such courses, ready-made after careful consideration, would constitute a boon to a very wide section of American industry.

Conclusion

It has been the purpose of this section only to draw some attention to the immense importance of border-line fields of research in our national scene, and to attempt by citing a few specific industrial examples further to emphasize and delineate the picture. There

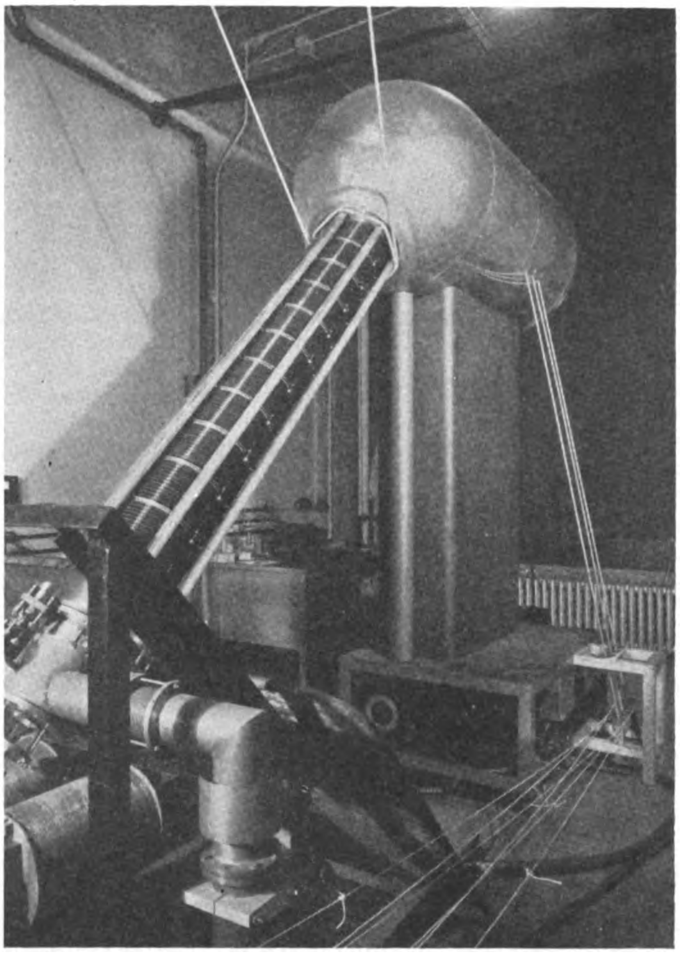

FIGURE 103.—Source of Pure Beams of Protons for Biophysical Research

is little doubt that in many respects the worker in border-line fields represents the spear head of research. The consolidation and coordination of scientific information from many fields and the welding of it into a powerful new tool to attack new and important regions of the unknown has always been a tendency of any youthful human endeavor. The worker in border lines is a pioneer, and as such an immense national resource. As such, too, he faces the grave disadvantages of lack of suitable training facilities and often the lack, at least temporarily, of any suitable professional status to assure that slight measure of prestige among his fellows which is often necessary to perform good work. Whatever can be done in the future to supply him with both of these highly essential working tools will contribute enormously to the preservation and enhancement of one of our greatest sources of national wealth.

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SECTION VII
APPENDIX

Contents

SECTION VII

1. THE RELATIONSHIP OF THE NATIONAL RESEARCH COUNCIL TO INDUSTRIAL RESEARCH

By **Albert L. Barrows**
Executive Secretary, National Research Council, Washington, D. C.

Relationship to the National Academy of Sciences

The National Academy of Sciences, of which the National Research Council is an operating agency, is a body of some 310 eminent scientific men of the United States, organized in 1863 at the request of President Lincoln, and chartered at that time by Congress to advise the Government in scientific and technical matters. Its charter, in part, reads as follows—

> . . . the Academy shall, whenever called upon by any department of the Government, investigate, examine, experiment, and report upon any subject of science or art, the actual expense of such investigations, examinations, experiments, and reports to be paid from appropriations which may be made for the purpose, but the Academy shall receive no compensation whatever for any services to the Government of the United States.

Since its establishment the National Academy has taken a place as a body of distinguished scientists of the United States among the scientific societies of the country. Its function, also, as scientific adviser to the Government has been continued through response to requests from time to time and this function has, in fact, been much increased in recent years.

When in 1916 it became apparent that the United States could hardly escape being drawn into the First World War, the Academy made special tender of its services to the Government, and at the request of President Wilson organized, as a measure of national preparedness, a special advisory body in the form of a large committee, with a number of subcommittees, to which was given the name of National Research Council. This Council was composed of scientific men and engineers who were themselves associated with educational and research institutions and industrial corporations. The Council served the Federal Government during the First World War in coordinating and making available to the Government the research resources of nongovernmental institutions and in bringing these resources to bear upon urgent scientific problems of munitions, of military equipment, of public health, of food and nutrition, and of other exigencies of the emergency. During this time the Council acted as the Department of Science and Research of the Council of National Defense, and as the Scientific and Research Division of the Signal Corps of the Army. The Council had numerous contacts, also, with the Navy Department and with other governmental agencies in connection with scientific war problems.

Upon the close of the war the National Research Council was perpetuated by the National Academy of Sciences, again at the request of President Wilson, expressed in an Executive Order (No. 2859, May 11, 1918). The continuing purpose of the Council is—

> . . to promote research in the mathematical, physical, and biological sciences, and in the application of these sciences to engineering, agriculture, medicine, and other useful arts, with the object of increasing knowledge, of strengthening the national defense and of contributing in other ways to the public welfare, as expressed in the Executive order of May 11, 1918 (Articles of Organization, National Research Council, Article I).

In order to carry out this purpose and to coordinate the major organizations and institutions of the country in the support of scientific research, the Council is composed of representatives of about 85 national scientific and technical societies. These society representatives constitute the greater part of the membership of the Council. In addition, many of the scientific bureaus and agencies of the Federal Government are also represented in the Council by Presidential designation, and a limited number of members are chosen at large. The total membership is about 220, including many men from fields of engineering and from industrial research laboratories. This membership is grouped into 9 divisions representing the major fields of science and certain general interests of the Council in the international relationships of science and in the educational aspects of research. Within these divisions are organized a large number of committees, the membership of which brings about 1,150 additional persons into active association with the Council.

The National Research Council may be regarded, therefore, as an operating agency of the National Academy of Sciences, organized to assist the Academy in carrying out its prescribed functions and to relate the Academy to many other scientific and technical agencies of the country for the purpose of advancing scientific research in the United States. For these purposes the Council brings to the Academy recognized contacts with a great many of the research organizations and institutions of the country, and in addition the Council is provided with executive officers whose business it is to effect timely encouragement of research in the major fields of science.

When the National Resources Planning Board requested the National Research Council in the spring of 1939 to make a study of the capacity of industrial corporations in the United States for scientific research, and especially the trends of the research undertaken by the laboratories of these firms, the Council recognized this as a major problem affecting all fields of science, and made this study an enterprise of the Council as a whole. To take immediate charge of the study the Council appointed a committee of 26 members, in addition to a Director for the study and a staff of several associates. By the time the report upon this study is finished work upon it will have occupied the greater part of a year.

Relationship to Research Agencies

The Council has always recognized the research institutions of industry as an important part of the whole research resource of the country. These industrial research agencies have increased very greatly, both in number and in the extent of their operations, during the past 25 years. This is shown in a general way by the increase in the number of firms maintaining laboratories as a part of their establishments from about 300 in 1920 to over 2,200 in 1940. Many of the men who have contributed largely to scientific progress are engaged in industry, and a very considerable portion of the membership of the National Research Council is drawn from industrial circles.

The changing proportions within recent years of the relative parts which each of the major groups of research agencies (educational, governmental, and industrial) play in the progress of science is in itself significant. The colleges and universities which are the traditional abode of learning, and which still continue to contribute strongly to the increase of knowledge through research, have, however, the additional peculiar function of training scientific personnel for research work of all the other types of scientific institutions. The Federal Government, and to some extent the State governments, have been obliged to expand their research facilities greatly in order to provide the information needed to perform their administrative functions in law enforcement and in the promotion of public welfare. Many lines of basic research, also, can only be undertaken by agencies equipped with such authority or facilities as the Government inherently possesses. There has, therefore, been a great expansion of the scientific work of Government agencies in recent decades In industry the urge for the greater and greater use and development of additional systematic knowledge to apply in the useful arts is mainly, if not wholly, activated by the desire for ultimate financial profit. This urge is sharpened by competition not only within an industry but also between industries. It has been a very potent factor in the development of special research agencies in industrial enterprises, and these agencies have added in constantly increasing measure to the store of fundamental and applied scientific knowledge. Although precise figures are lacking, it is easily recognized that, while money spent for university research has increased markedly during these years, this increase has not been nearly so great—either proportionally or absolutely—as the increase of funds devoted to scientific research by industrial establishments.

The Council has aided the Academy from time to time in solving the scientific problems referred to it by Government agencies, and the Council has been enabled through large funds placed in its hands to assist the research work conducted in educational and special research institutions by means of research grants. The Council has also attempted to aid in advancing the types of research which are developed in industry, as well as in strengthening industrial research capacity. This has been done both by direct action upon selected research problems arising in certain industries, and also by organizing studies of conditions attending the progress of research in industry.

The research enterprises in which the Council was engaged during the First World War pertained largely to problems relating to supply of military matériel, and a number of these projects were carried over under the permanent organization of the Council. These included continuing problems in various industries; such as heat measurement, steel-making processes, heat treatment of steels, production of high-speed tool steel, hardness testing, fatigue of metals, welding research, prime movers, fertilizers, synthetic drugs, ceramic research problems of neurology and psychiatry, and medical problems of industry.

Relationship to Industry

In the report of the National Research Council to the Council of National Defense for the years 1918 and 1919, the following paragraphs occur:

> One of the most striking consequences of the war is the increasing general realization of the primary importance of scientific research to the whole question of national defense, as well as to the successful prosecution of industry and the greatest measure of economy of resources after the war. The necessity of research work as the only means of solving many military and industrial problems has been realized fully in many foreign countries where, despite the stress of war and of the excessively heavy burdens imposed by it, very large sums have been appropriated for its promotion and support.

Impressed by the great importance of promoting the application of science to industry in this country, the National Research Council took up the question of the organization of industrial research in the belief that this matter should be furthered in every way possible and as rapidly as may be. The National Research Council considers that cooperation among capital, labor, science, and management constitutes the best general means of financing and directing the extended laboratory investigations and the large scale experimental and developmental work required for adequate industrial research. Accordingly it inaugurated an Industrial Research Section to consider the best methods of achieving such organization of research within an industry or group of related industries.

On this basis place was made in the permanent organization of the Council for an agency to serve the research interests of industry. It was felt at first that there was need in many industries for an increased appreciation of the value of research in industrial development. In the years immediately following the First World War much of the attention of the Division of Engineering and Industrial Research of the Council, and of a Division of Research Extension (maintained in the Council for several years for this express purpose) was devoted to encouraging a recognition in industrial circles of the importance of making research a guide in manufacturing processes and in the supplying of new and attractive products.

This function has been carried out in various ways in addition to the study of direct research problems in industry. For instance, a number of conferences have been held for the consideration of the important potential relationships between industry and the universities in research matters. These relationships consist in part of means for utilizing university research facilities for work upon fundamental research problems, and the draft upon universities for the training of scientific personnel in industry. In the opposite direction, also, industry has a distinct contribution to make to university research work through intrinsic additions to knowledge and through the stimulus that comes to research and the sharpening of its focus from the insistence of manufacturing needs and operations. It is distinctly a two-way cooperative relationship.

Through its Division of Engineering and Industrial Research the Council has also conducted special studies of such matters as the effect of the depression of 1930 and subsequent years upon the course of research in certain industries. It has encouraged the publication of volumes commenting upon the industrial research situation, such as Profitable Practice in Industrial Research, and Industrial Explorers. Representatives of the division have frequently appeared before trade associations to encourage applied science.

This division has conducted a number of tours to selected industrial research laboratories in the United States and one such trip to visit laboratories in Eng-

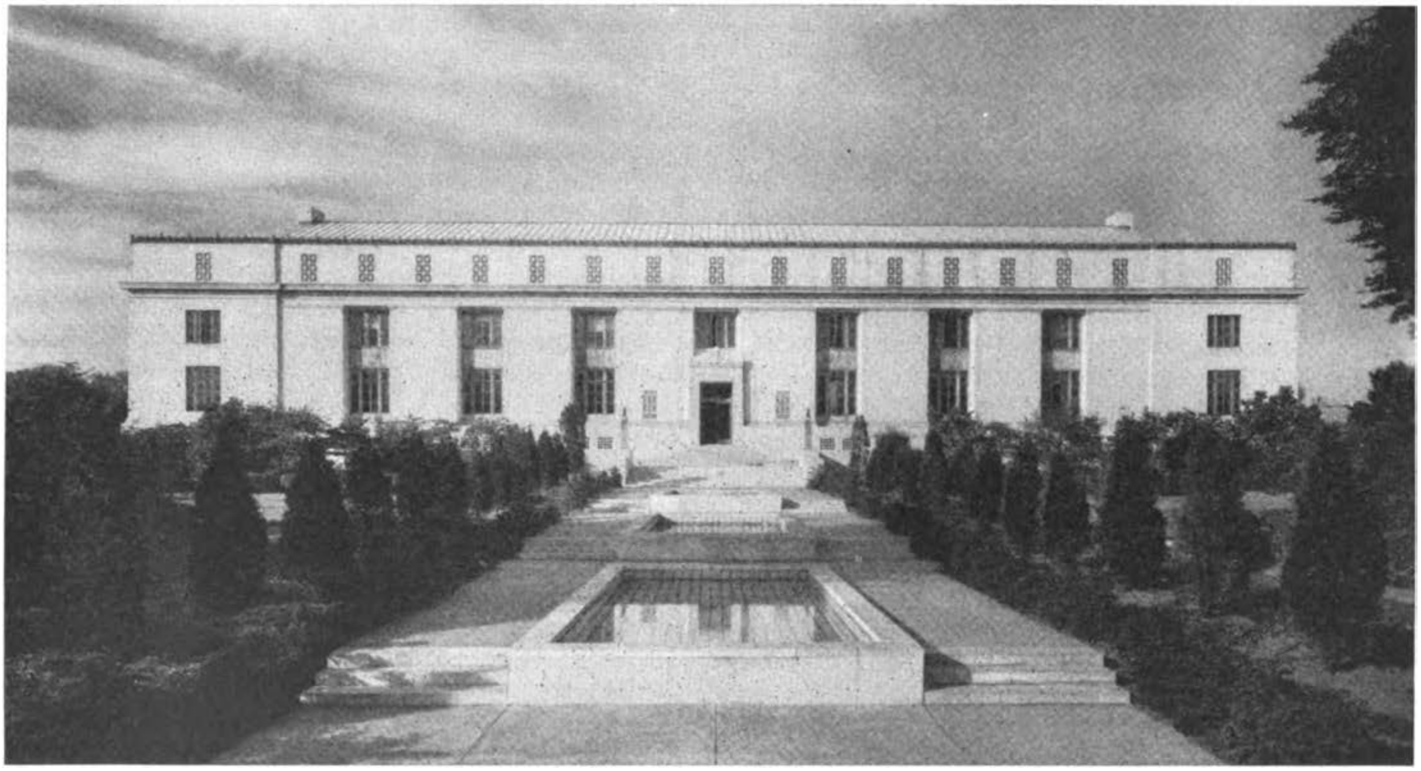

FIGURE 104.—National Academy of Sciences and National Research Council, Washington, D. C.

land, Germany, and France. These were organized to give industrial and financial executives an opportunity to see how certain successful industrial research laboratories have been set up, what their work consists of, and how this scientific work has been built into the organization of these companies. The division has had numerous advisory contacts also with many industries and individual corporations during the past 20 years.

In other parts of the National Research Council, also, relationships with industry have been developed and, through the Council, industry has itself contributed in important ways to the general progress of science in this country. Most notable perhaps of these contributions from industry was support (totalling over $84,000) given by a large number (about 180) of industrial concerns to the publication of the International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, issued by the Council during the period from 1926 to 1933; and the subsequent contribution by many corporations to the Annual Tables of Constants and Numerical Data of Chemistry, Physics, Biology, and Technology, published in Paris.

Groups of firms in various industries have from time to time made use of facilities offered by the Council for coordinating research effort upon scientific or technical problems arising in those industries. Large contributions in funds, in services, and in apparatus have been made by industrial firms to the Council for the support of such projects. In engineering these have included, for example, investigations upon electrical-core losses, heat transmission, the preservation of marine piling, fatigue phenomena of metals, industrial lighting, and highway construction and management. Industry has contributed, also, to research undertakings sponsored by other divisions of the Council, such as studies of pyrometry, colloids, catalysis, ring systems in chemistry, chemical economics, petroleum geology, the chemistry and pharmacology of narcotic drugs, food and nutrition, reforestation and germination, agricultural uses of sulfur, the standardization of biological stains, diseases of Cuban sugarcane, and problems of personnel in industry. The auspices of the Council have been utilized for a number of years to hold a series of conferences on electrical insulation and for other conferences in which industrialists have frequently joined with academic scientific men. Industry has also contributed through the Council to the support of research undertakings bearing less directly upon industrial problems, as for instance, an extended program of research upon the biological effects of radiation. Certain other projects of the Council have contributed more or less directly to the support of industrial science, such as the publication of an Annual Survey of American Chemistry over a period of some 10 years. The Council has also administered considerable funds supplied by industrial corporations for investigations carried on by the National Bureau of Standards as a part of the cooperative program of the Bureau for service to industry. Of the post-doctorate fellows appointed by the Council during the past 20 years in the fields of chemistry and physics, over one-sixth (89) are now engaged in industrial work and several past fellows of the Council in medicine or in the biological sciences are connected with industrial operations.

During recent years it has seemed on the whole that the attitude of industry toward research has changed. The value to industry of progressive and often exceedingly broad and fundamental research has come to be more and more generally recognized. Financing concerns are paying attention to the research policies of the corporations to which they lend aid. Attention has accordingly shifted from the question of undertaking any research program at all to the conditions under which research, set up as an accepted part of the industrial establishment, may guide industrial development with increasing efficiency and profit.

Division of Engineering and Industrial Research

Taking advantage of this turn of interest it was possible for the Council's Division of Engineering and Industrial Research two years ago to organize an Industrial Research Institute, composed of member firms which contribute funds for the support of the work of the Institute. The objective of this organization is to provide a forum for the study and discussion of problems of common interest affecting the utilization of science for industrial purposes. These problems include such matters as sources and training for scientific personnel, job analysis in the laboratory, relations of the laboratory to the production and sales departments in different types of corporations, financial incentives, patent policies, and the various relationships between universities and industry in matters of research.

In the structure of the National Research Council many of the direct relationships and obligations of the Council to scientific work in industry are represented through the Council's Division of Engineering and Industrial Research (which has its offices with a full-time staff in the Engineering Societies Building in New York City). In order that the Council may be able to discharge its functions in industrial fields, this Division has recently been reorganized and its membership now consists of three parts, a third representing the engineering and technical societies of the country, of which some 18 will in rotating course be represented from time to time, a third selected from the membership of the Engineering Section of the National Academy of Sciences, and a third selected at large, totalling 27 members altogether, and including university men, directors of industrial laboratories, men of affairs, and industrial and financial executives. The Division is constituted in this way in order to be widely representative of all scientific interests affecting industrial progress and able to view not only advancement of research in industry, but also the long-range relationships of this advance to its benefit to industry itself, and to its responsibilities to the social and economic welfare of the country and of the Government.

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SECTION VII

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Research laboratories sent illustrations which have been inserted as presenting pictorially some of the physical facilities and aspects of industrial research. Space limitations necessitated omission of much interesting and valuable pictorial material, and, obviously, only a few of the 2,264 laboratories could be represented. Selections were made from photographs readily available and suitable for publication, and which serve the desired purpose.

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To a large number of individuals who have contributed generously of time and effort the Committee feels that it has great obligation. Without this cooperation the report could not have been compiled.

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U.S. National Resources Committee
Science Committee.
Research - a national resource.

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