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Preface

If one compares the world of today with that of one or two decades ago, it is clear that modern science and technology have become profound influences on economies, societies, and international relations. This process certainly will continue, and may accelerate. It will deeply affect American foreign policy, whether with friends or adversaries, competitors or collaborators, rich or poor.

Against this background the National Academy of Sciences, the National Academy of Engineering, and the Council on Foreign Relations decided to bring together members of their respective constituencies to begin addressing foreign policy implications of technological change. We viewed the effort as an opportunity not to answer questions, but to raise issues and to heighten consciousness.

The process of preparing for a symposium on technological frontiers and foreign relations, from which the papers in this volume were drawn, was a protracted one. Over a period of 2 years, the authors of the presentations met for discussions among themselves and with other individuals of diverse backgrounds. The technological forecasts were prepared and reviewed first. Papers discussing the impact of technological futures on foreign policy were drafted during a second round of discussions.

We were especially fortunate to have enlisted a unique chairman for the symposium, Allen E. Puckett, Chief Executive Officer and Chairman of the Board of Hughes Aircraft Company, and one of the few individuals who is a member of all three sponsoring organizations.

Others who participated in the preparatory efforts included: John M. Deutch, William Diebold, Jr., Harald B. Malmgren, Joseph S. Nye, Jr., Henry Owen, Elliot L. Richardson, Eugene B. Skolnikoff, John D. Steinbruner, and Alvin Trivelpiece. We would like to recognize the outstanding contributions of the respective staff members of our organizations, including Paul H. Kreisberg, Margaret Osmer-McQuade, and Harry C. Blaney III, a visiting fellow from the Department of State, at the Council on Foreign Relations, and Nancy Gardner Hargrave and Paul Uhlir of the National Academy of Sciences.

We also wish to express special appreciation to the symposium director, Anne Keatley, who conceived and directed the effort throughout.

FRANK PRESS
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National Academy of Engineering

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Technological Frontiers and Foreign Relations

Introduction

THE INTERPLAY of science, technology, and foreign relations is a primary issue of our times. Foreign policy questions with major technological components now rank with territorial and ideological concerns in international debates. It seems that Winston Churchill's prophecy has come true: "The empires of the future are the empires of the mind."

What will these empires be like? Will genetic engineering so advance agriculture in arid and tropical climates that poor nations become able to produce enough food for themselves? Will materials and biotechnology research in university laboratories today have commercial applications in the next 5 to 10 years?

What might such advances mean for the international community? What policies and practices are being devised at home to assure that science and technology support our objectives for military and economic security, expanded employment opportunities, improved public welfare, and national prestige? What will be the impact of what we do on our allies and adversaries? What do they *think* it will be?

These are some of the broad questions that surround the main issues of technological advance and foreign relations—industrial competitiveness and economic growth, military security and the push toward locating strategic defense systems in outer space, impediments and incentives to technology transfer, population growth and distribution, and food and nutrition. New concerns are appearing on the horizon as the already pervasive influence of advanced technology on economies, societies, and relationships among nations continues to intensify.

Establishing an analytical framework for the highly complex interactions that underlie such issues requires an interdisciplinary effort. The symposium on which this book is based was a first step in bringing together leaders from high-technology industries, banking and finance, the law, labor, government, and the university and foreign policy communities to consider these interactions.

Participants in the symposium examined trends in advanced technology; how these trends affect the economic and security interests of advanced industrialized countries; relations among those countries, and between them and the Soviet bloc and the developing nations; the relevant present and prospective policies of governments; and the consequences and efficacy of alternative policies.

IMPLICATIONS OF TECHNOLOGICAL DEVELOPMENTS

An analysis of the effects of advanced technology on international relations must include an estimation of the continued rate and direction of change of the relevant technologies. Forecasts in telecommunications, computers, aeronautics, materials, energy, and biotechnology indicate that broad technological trends rather than radical new developments will affect relations among nations during the next 2 decades. The following extrapolations from the forecasts consider likely economic, social, and political implications of these trends.

Telecommunications

Modern telecommunications technologies are transforming open pluralistic societies—we have entered what many describe as the information age. In the political sphere telecommunications will support the trend away from representation to a form of popular participation. Politicians may seek direct feedback through polls and surveys. Widespread use of electronic referendums for direct democracy will be possible. It will be harder for governments to separate audiences by conveying one message to the domestic public and another to leaders abroad. The result may be less duplicity but more ambiguity in government positions on various issues.

On the international level, global political figures may emerge. The national leadership in one country may be able to get direct assessments of political sentiments around the world, thus allowing the creation of transnational constituencies. Political groups may increasingly gain worldwide recognition of their causes via the electronic media. Organized crime and terrorism could become more international, but so could law enforcement.

For highly structured, sequestered societies information technologies present a dilemma. Telecommunications has a decentralizing effect, which is at odds with the centralized control of information that characterizes such societies. The spread of advanced telecommunications technologies will hinder efforts to restrict communication through traditional methods such as jamming broadcasts or wiretapping telephones. Yet any attempt to limit the use of these technologies will increasingly place closed societies at a competitive disadvantage compared with the open information societies of the West.

For developing nations modern telecommunications will continue to improve delivery of health care and educational services. A significant point of conflict, however, is the use of equatorial geosynchronous orbits for communications satellites. Because there are only a limited number of slots available in that orbit, developing nations are concerned that by the time they possess the requisite technology and need for exploiting the medium, the industrialized nations will have already appropriated all of the available slots. Some developing equatorial states have already made claims on the "sovereignty" of the geosynchronous orbit area 22,300 miles above their territories.

Computers

The primary trend in complex computations is one of increased speed hand-in-hand with reduced costs. Together with a continuing decline in transportation costs, these developments will significantly change the processes of production and distribution of goods and services, although these changes may not be completed by the turn of the century.

Computer-aided design along with robots that can be reprogrammed to do more than one set of tasks will permit small, specialized production runs around basic designs. Cheap and reliable transportation will permit products to be shipped from relatively few points so that production can take place almost anywhere. On both counts, there could be a dramatic reduction in the need for inventories in the production-sales sequence, thus conserving capital. Moreover, consumers could be offered greater variety at mass production prices.

With low-cost/high-volume communications, the service industries will be transformed. The physical location of retail outlets for financial services and even goods will make much less difference than at present. There also will be heightened interest in business cryptography to keep information out of the hands of electronic eavesdroppers.

In Soviet bloc states the influence of computers is not as pervasive as it is in the West. Only in the military do computers have widespread applicability. In terms of economic use, the computer generally is limited to the principal government bureaucracies and research centers. It is used little in education and has virtually no home or consumer applications. Here, as in telecommunications, the dilemma posed by advanced computational technologies is economic efficiency versus political control. To allow people to use computers and communications networks in the privacy of their homes could fatally weaken central government control.

The great reduction in costs and the wide versatility and utility of computers make them ideally suited for technological transfer to the developing countries. The People's Republic of China may invest heavily in computers, particularly if the Chinese leadership continues its pragmatic policies aimed at economic modernization.

Materials

One important contribution of new materials will be the conservation of energy. This will be done partly by the use of lighter metals and partly by improvements in production through computer-aided design and manufacturing.

Demand may drop for some of the traditional materials such as steel, copper, and aluminum, putting strains on existing industries that already suffer from world excess capacity. In the near future, protectionist measures in these sectors may especially affect net suppliers such as Brazil and the Philippines. Also, the substitution of new materials for old ones will depress the earnings of ore producers worldwide.

The U.S. strategic stockpile plan, designed to ensure the availability of materials in case of disruptions, may have to be drastically revised by the mid-1990s, if it is to remain useful. It also may require a radical alteration of concept, to encompass not materials themselves, but rather the capacity to switch from one material to others that are close substitutes.

It is in relations with developing nations that advances in materials may have the most dramatic effect. The developing countries, or the

"South," take an ideological approach to many international issues. In the area of technology and resource development, this approach is nourished by two primary concepts. The first is the concept of the "New International Economic Order" (NIEO), that is, that the industrialized democracies (the "North") composed of former exploiters and colonizers, owe restitution to the developing South for past transgressions. The second is that of the "Common Heritage of Mankind," a euphemism for socializing natural resource development on a global basis with central planning controlled largely by the source countries—that is, by the South. These concepts have significant impact on the North's ability to obtain rare or strategic materials.

Aerospace

There will be continual improvements in transportation, especially by air, as a result of advances in materials and computer technologies. Reductions in weight and cost will be made, controls improved, all-weather landing capacity facilitated, engine efficiency increased, and distance potentially covered in less time. The price of air transport will consequently continue to decline.

It is in the application of weapons technology to space that the West faces the strongest challenges from the Soviet Union. The development of military systems in space, including the new "strategic defense initiatives," is a topic of intense international debate. The technologies in this area represent a synthesis of all the most advanced aspects of other technologies discussed here, except for biotechnology. It is certain that military space technologies will become increasingly important in the context of the East-West balance of power. Issues raised by the development and use of these technologies may replace nuclear weapons as the primary defense topics in the 1990s.

The potential for significant use of outer space by the turn of the century, except for telecommunications, scientific experiments, and military purposes, is a subject of debate. The widespread perception that space may be commercially important, however, may ensure considerable expenditures in applicable areas by major governments.

Energy

Since 1973 the more developed countries have dramatically reduced energy use in all sectors, especially in manufacturing. The trend of energy use reductions relative to total production in those economies should continue. Nevertheless, economic growth will increase the demand for energy, particularly in the developing countries. Thus there may be steady progress in limiting increases in the demand for oil, but overall reductions by the turn of the century are not likely.

One problem is the time it takes to bring on line new systems of energy with substantial magnitude. The current weakness in oil prices has delayed conversion to coal and the development of shale oil. Lower prices also inhibit investments in the development of new energy source technologies. Continuing U.S. vulnerability to disruption in oil supplies will become apparent should the world market tighten again. This vulnerability could represent a feature of the world economy and a concern for foreign policymakers in the 1990s.

Looking beyond this century, the relative importance of coal seems likely to grow, with the United States being the major supplier and other industrialized democracies being the major buyers. This will require public-private cooperative financing of infrastructure, including transportation, energy, and water.

Energy is one area that could offer opportunities for East-West trade and technology transfer. The Soviet pipeline project, designed to supply natural gas from Siberia to Western Europe, has generated considerable friction between the United States and its European allies. It is doubtful that the United States will cooperate with the Soviet Union or transfer technology for energy resource development in the foreseeable future. Nevertheless, the possibility for some cooperation on peripheral issues, such as nuclear nonproliferation and safety regulations, does exist. Eastern Europe, like most of Western Europe, is a net energy importer. East European governments are consequently seeking not only new energy sources but advanced technologies for energy generation, conversion, and conservation. Apart from the Soviet Union, they may also successfully seek to obtain technology from Western Europe that is not critical to defense.

Nuclear weapons proliferation continues to be a primary issue associated with the energy needs of developing countries. The International Atomic Energy Agency (IAEA) predicts that by the end of this decade 40 states will be using plutonium to fuel their nuclear power plants. The nuclear nonproliferation agreement, administered by the IAEA, is perceived to have basic enforcement flaws. Moreover, several developing nations, including the People's Republic of China, do not participate in the treaty. This has been a major stumbling block in U.S. willingness to provide China with nuclear power plants.

Biotechnology

Biotechnology—through the techniques of genetic engineering—has brought the world to the threshold of a new agricultural revolution. The main beneficiaries could be the food-importing developing countries, if their infrastructures can accommodate the necessary changes.

Such a shift toward self-sufficiency on the part of developing nations could profoundly alter world trade in agricultural products. Both Europe and the United States already bear the burdens of agricultural surpluses and price supports. The increase in food output by developing countries promised by agricultural applications of genetic engineering may further exacerbate these problems by diminishing the export market for industrialized nations.

Advances in health care resulting from biotechnology also may have far-reaching effects. The increase in the average age of the population will encourage major changes in current labor market practices, such as the setting of mandatory retirement ages. Intergenerational conflict may increase in the industrial democracies until acceptable new work patterns can be developed. In addition, medical progress through biotechnology may outpace agricultural advances, creating gaps and shortages that could affect immigration trends.

In the East-West context, the vast potential of biotechnology raises many issues. The Soviet bloc states are likely to be innovators and producers to the point of successfully competing with the West in world markets, primarily in the areas of health and agriculture. International regulation, standardization, and oversight will be important to ensure a modicum of safety. However, competition in biotechnology may also take place in the military establishments, thus creating a major impediment to the implementation and enforcement of worldwide safety regulations.

ADVANCED TECHNOLOGY AND THE INNOVATIVE PROCESS

The projections presented above are based on factors that can be better appreciated through an understanding of the nature of advanced technology and the activities described as "the innovative process." The capacity of the United States for technological innovation is commonly perceived in terms of industrial sectors—microelectronics, computers, new materials, robotics, telecommunications, aerospace, and now, biotechnology. However, the list is continually changing. Thus advanced technology must not be thought of only in terms of specific products, but as a continuous process, widely diffused throughout an economy, to produce and use scientific knowledge and technological expertise. The process is manifested primarily in a system of interrelated activities leading to commercial sales of products. This, then, is "the innovative process"—a highly integrated system spanning education, research and development, manufacture, marketing, and distribution. The following description is worth review.*

Research—whether in a university setting, in research institutes, in government laboratories, or in industry—generates new scientific knowledge and new ideas for application. One innovation leads to another by suggesting new directions for further technological investment. In industry, company interests usually dictate research; in universities and research institutes, individual scientists choose whatever scientific leads they deem both important and capable of attracting financial support.

Development—translates a new discovery or idea into a usable product at a defined market demand. It encompasses the steps between research and completion of the design of a product. It includes a validation phase, where elements emerge from a research environment to one having risk low enough to permit their use in a product, and an application phase which integrates such elements into a product design suitable for production. The former frequently proceeds before the application product is known, and certainly long before it is defined. The latter phase, application, occurs after the product is known. It can include prototype or pilot scale tests on either product or process. Development responds both to research results and to feedback from the marketplace.

Manufacture or Production—takes the product or process from a single prototype to quantity production that promises the consumer reliable quality and controlled cost. The line between development and manufacturing is expressed in the comment that it's always possible to make *one* of anything; regular production demands reliability, competitive costs, serviceability, often retooling of the manufacturing plants, setting an enforcing criteria for suppliers, and more.

Distribution—entails marketing, delivery, customer training, and support services. It addresses the requirements of the consumer in using the product.

*From *The Race for the New Frontier, International Competition in Advanced Technology—Decisions for America*, National Academy Press/Simon & Schuster, New York, 1984, p. 25.

This system—what it is, how it works, what influences it, and what is necessary for its strength—is the framework for governments' policies on technology and industry.

INTERNATIONAL COMPETITION IN ADVANCED TECHNOLOGY

Governments of industrialized Western nations use a variety of instruments to support innovation. Traditionally, the primary role of the United States in fostering nations' innovative capacity has been the support of research and higher education. There are other important measures, however. Tax policies may encourage investments in research, development, and production facilities or may affect the availability of venture capital. Education policies and practices at all levels help meet manpower requirements for technologically sophisticated managers, quality research personnel, and technically skilled factory and office workers. Other instruments include patent laws, regulation and deregulation, antitrust measures, export/import bank loans, and government procurement.

The actions of one nation to support innovation may be perceived as imposing unacceptably on the interests of another. The United States and its allies, most notably Japan, are deeply divided over respective national policies to support industrial competitiveness—policies that may endanger the international trading system, political alliances, and global technological progress. One point of contention, for example, is national efforts both to establish market penetration abroad and to resist penetration by others at home.

Advanced technology industries require large, immediate markets to recoup large initial research and development costs. The United States is an important market for other nations and has few barriers to penetration. The Japanese market also is significant, yet its resistance to outside suppliers is a continuing source of friction in U.S.-Japan relations. Markets in developing countries are of increasing importance. A variety of governmental actions adopted to capture them—associated technical assistance, political support, trade deals, and offers of nuclear and other technologies—may have significant international consequences.

In some cases, a nation's technology policies may be deemed detrimental by both foreign and domestic parties. Domestic constituencies also have questioned export controls on the grounds of their potential negative effect on U.S. industrial competitiveness. There is concern that as other nations move toward technological frontiers, the United States may no longer have the influence to determine the profile of East-West trade. The consequence may be loss of U.S. sales without the achievement of desired foreign policy objectives.*

IMPEDIMENTS AND INCENTIVES TO INTERNATIONAL TRANSFER OF TECHNOLOGY

The United States imposes controls on transfer of technology with military applications, both products and expertise, to Soviet bloc and other adversary nations. Control is exercised not only on U.S. activities, but also on those of other countries. U.S. attempts to so regulate the trade of others are a sore point in relations with Europe and Japan. Europe's extensive trade with the Soviet Union and Eastern Europe, involving exports of industrial plants and machinery and imports of energy, is considered economically essential by European nations. A comparable situation exists in Japan, where economic and trade relationships are part of a broadly defined strategy for national security. U.S. pressures to restrict advanced technology trade with the Soviet bloc for military and foreign policy reasons thus pose fundamental problems for its allies.

A NEW TECHNOLOGICAL PROTECTIONISM?

East-West tensions over technology transfer policies—now well understood but still difficult to address—may be aggravated by new trends in the United States toward "technological protectionism." The links between scientific frontiers in the laboratory and economically valuable product and process developments are becoming closer. Scientific research conducted in universities and national laboratories is becoming fundamental to industrial productivity and competitiveness. The traditional accessibility to foreigners of the U.S. educational and research system is, thus, more and more frequently questioned. Major research universities are considering denying European and Japanese students access to the most advanced projects, for example, in areas such as artificial intelligence. Scientific societies are limiting some meetings to U.S. citizens only. Questions of balance and

**Ibid.*, p. 47.

reciprocity are being raised about foreign access to frontier biotechnology research in federal laboratories.

These events could be aberrations or they could be the beginning of an "intellectual isolationism" stemming from a desire to ensure U.S. technological leadership. If the latter, such trends would further strain U.S. relations with allies and could affect the free and open flow of ideas considered fundamental to the health of the scientific endeavor.

CONCLUSION

The ways in which countries attempt to support, protect, and use new scientific knowledge and technical expertise profoundly influence international relations. Technological issues are standard agenda items at economic summits, in bilateral discussions, and elsewhere in the international community. It is hard to imagine future trade negotiations without advanced technology occupying a special status. Congressional debates on antitrust legislation, the Export Administration Act, the creation of departments of trade and science, protectionism and extraterritoriality all have at their core technology and concern about the nation's technological capacity.

The political problems of multinational corporations, the many gray areas of East-West technology transfer that plague the industrialized democracies, and the aspirations of the developing world to share if not to avoid injury by advanced technology all ride on the relentless, accelerating progress of science and technology, a process leading to the possibilities of new industries, revitalization of old industries, new military systems, new ways of producing food, and better health.

This is not the first time that the development and use of new technology has had consequences for national interests. We have dealt with this situation for almost a century. But the *pace* of modern scientific and technological advance is unprecedented. All nations want to share in this new industrial revolution, and that, of course, is the basis for new international problems. How they respond will determine their futures and the future of the international community.

The Foreign Dimension of National Technological Policy

Simon Ramo

MOST INTELLIGENT PEOPLE (the more perceptive ones for thousands of years, probably since the invention of the wheel or the first control of fire) have looked at advancing technology's impact on society and assessed it as potentially extremely consequential. Advancing technology, they have realized, would radically change society.

Today it is clear that the impact has become so deep and pervasive and the changes are coming so rapidly that all of our organized ways of approaching national and international social, political, and economic adjustments are suddenly out-of-date. Our ability to respond is in jeopardy. It is incumbent upon us to recognize this as we try to understand what the technology impact is all about.

We all know that the big changes, the big issues of the day as the public sees them (and hence as the political leadership of the nation sees them in response to the public), are social, economic, and political. They are things like curbing inflation, deficits, unemployment, trade imbalances, the cost of health care, or crime in the cities.

These are not science and technology issues, yet all social, economic, and political issues intersect; and at each intersection are science and technology aspects—influencing what happens, introducing problems, introducing potentials for solutions, and introducing new possibilities for the way things will have to be done.

One key impact of technology on society is the way it is altering international relationships. This shows itself conspicuously in world trade. International trade has been developing in two contrasting and contesting ways: One is a kind of one-world, or free-trade, concept in which ideas, products, raw materials, money, and even people move across borders freely. This approach always has the potential of producing economic advantage for everyone, each segment of the world doing what it does best as a contribution and then partaking of what the others have to offer in return. Competing with this one-free-world idea is the protectionist, isolationist, nationalist approach. Here, each entity, dominated by its domestic social-economic-political problems, makes an effort to beat the system, trying to control international flow and reap some advantages from that control. Probably even the youngest person at this symposium will not live to see the end of the contest between these two approaches. Probably we will always have a mixed approach. However, I think it is important to note that technology advance is giving great impetus (and this is not generally recognized) to the power of the first approach, the free-world-trade route.

Almost everything important in trade now depends upon technology. Technology (products and know-how) is rapidly becoming the champion area of trade. Even such export-import items as raw food products and crude oil, which may at first thought appear to be properly categorized as nontechnological products, are tied to a technological base. Thus, without our mechanical and chemical technological advances, we would not realize the trade surplus in food that accrues to America. Crude oil trade and all that goes with it—the way it affects national policies, strategies, negotiations, and security—results from building our highly technological world around the use of vast amounts of petroleum.

The present all-out international technology race will exert a powerful influence on world trade. The "technology Olympics" is far more important to the world than the other Olympics. Every nation now perceives its economic development, social stability, and national security to be highly dependent on its stature in technology. Each nation, accordingly, is avidly seeking to develop its technological resources.

The nations' governments see the tool of technology as providing a means to increase production, reduce the cost of production, use less critical and expensive resources, and develop new products that are so socially and economically desirable that they will justify and attract the investment to market and produce them and will create jobs.

The standard of living and the way of life of each nation are now regarded as determined largely by how that nation fares in the international technology race. To win events in the technology Olympics is to enjoy the fruits of technology advance and to be safe. To lose badly can be catastrophic.

All nations, with the exception of the United States, are convinced that effective use of technology, which is key to their future success, will depend upon how skillful they are at latching onto the technology that originates in other nations. Each nation knows that no one nation is big enough in terms of science and technology to attain the preeminent position that the United States has enjoyed in the past. Consequently, they are building their policies around the basic concept of acquiring technology from outside their borders. Only the United States assumes, despite the evidence that it is no longer true, that it has the technology and the other nations do not, and thus that it should build its policies around preventing other nations from acquiring U.S. technology.

Usually when the word *policy* is used, the policy referred to is that of the national government. It turns out that there is a lot more to policy than what the government does. A myriad of policy-related actions go on all the time in private as well as government sectors, and combined, they have an enormous impact on what really ends up being national policy. When I say "policy" in this broad sense, I mean selecting goals, deciding where resources should be placed, setting priorities, organizing for implementations, judging the results, and making strategy.

It has been true of the United States from its beginning that capital at risk married technology potential to create as offspring an enormous flow of technological products that changed America and the entire world. If this approach were enough, U.S. government policy would be simple. The government would merely have to enhance the free enterprise dimension. However, free enterprise is not the only consideration when it comes to using technology advances most advantageously. The policies of the world's governments are even more influential, but before we say why and how, let us consider the free enterprise area in the international sense.

Take, for example, multinational companies. If you happen to be associated with running such companies, it is impossible to overlook management's natural inclination to seek what is good for its shareholders. To the managers, goals and priorities are usually quite clear. At least their formation does not wait on the prior formation of pertinent government policies. Government policies are always late and often wrong. They are preemptable in important aspects by industry managements if those managements move quickly and early enough.

Forgive me for bringing up an illustrative incident out of my own personal experience with a company called TRW. About 20 years ago, while we were engaged in expanding our company to exploit our resources and potentials internationally, I was involved in arranging some deals with the Japanese. During the past decades, TRW has had some dozen joint ventures with Japanese companies. A typical pattern was that we became part owners of operations in Japan, we contributing mainly our technology and they contributing the money, and we received royalties on our technology. While negotiating, we knew that the new venture would increase the world market for our technology and that our Japanese partners would extend the technology base. We also knew that if we did not make the deal, they would do it without us a bit later, and we would end up with a shrinking participation in the total world market. (Some Americans have the impression that the United States "gave" technology away to the Japanese. Not so. We sold it, and we got a good price.)

It was straightforward internally to make decisions about these joint ventures. Nevertheless, I once went to the secretary of commerce and said, "Look, it is the job of TRW's management, right or wrong, to decide what we should do with the opportunity to set up ventures with the Japanese. We have technology advantages in certain areas. We can try to hold these advantages and not share our technology, or we can exploit our technology internationally. We are able to figure out, we think, what is best for our shareholders. But tell me, What is best for the United States of America? What policy would you like to suggest to me, even though it isn't official?" The answer was, "Gee . . . well . . . how would I know?"

I expected no expertise about electronics from the secretary nor judgments from him about the world market for technology. I did think I might hear some wisdom stemming from political expertise or a broad sense of where the nation was going and how to prevent problems from developing.

That was years ago. It is now clear that you cannot get answers to the kind of questions I was asking because the government is not organized around enunciating such answers. In the United States, goal articulation, basic to policy development, goes more to general political phrases (paralleled by the generation of a steady stream of vague subgoals with short lives) than it does to the calling out of focused objectives. Policy creation is always a systems problem. The numerous interacting and conflicting aspects should receive close integration, and many trade-off analyses and compromises must be carried out before balanced, harmonious policy can result. Yet all democratic governments constitute a large ensemble of agencies, each responsible for pieces of the whole. Such bureaucracies handle problems in piecemeal fashion—not as systems—with isolated attacks more common than integrated approaches. Diverse requirements must be brought together, but the compromising is mostly political, rarely objective.

Government policy is likely to be short-range, yet planning for the realization of the gains of technology demands long-range strategy. The leadership by government should preferably be direct and clear, but in a democracy it is more likely to be indirect and vague. Complex policy is best evolved not through the actions of a loose, huge organization but rather by a small group of exceptionally informed and capable people, possessing authority commensurate with their responsibilities, a situation difficult to arrange in a democracy.

Now, all of this may sound like the wailings of a scientist-engineer-industrialist who wishes that these very complex matters involving social-economic-political issues would be amenable to direct action—like running a straightforward engineering project or a private corporation—but I would submit to you, in defense, that nothing whatsoever contained in the Constitution of the United States bans long-range thinking or objectivity or the setting of goals. Such activities are not ruled out by law.

In fact, government sometimes does things right, albeit decades late. When you look back, you see that it could have been done earlier. An example: now, at last, after 15 years of hard effort (some of it by people at this symposium who did a lot of crying and shouting and complaining), the U.S. university situation in science and engineering is being improved. A reversal has occurred in federal budgeting for basic research (research budgets had been decreasing for years). We are also setting out to halt the decay of the engineering schools' facilities and equipment. (The neglect of engineering education has helped guarantee that the United States will have an increasingly smaller fraction of the world's engineers in the future and hence that we will be increasingly dependent upon technology from abroad.) Programs are being generated to encourage new young faculty, the teachers and researchers, to remain in the universities. We are beginning to build up novel, cooperative programs between technological industry and universities, and even among government laboratories, industry, and the universities.

All of these things are happening now in the United States, owing to strong leadership and push by people in the government, the academies, and industry. However, it could have been done 15 years ago. It has taken this long for the seriousness of the problem to penetrate, for enough people to understand the problem and then get into positions of influence. That pattern holds for anything else about technology policy that we might discuss.

I think, considering everything, that we must assume that all governments will permanently be late in both domestic and foreign technology policies. Let me cite two more examples—one very, very briefly, because it almost seems off the subject, although it really is a most pertinent example of the mismatch between accelerating technological advance and lagging social advance. I refer to the nuclear weapons race. The United States and the other superpower are planning to spend hundreds of billions of dollars in the next decade to double again their total nuclear offensive power, although the leaders of both nations have stated publicly (our own President in his State of the Union Address in January 1984) that there is no longer any use for nuclear weapons, except to deter those on the other side from using theirs. Since that standoff would work just as well (that is, be just as dangerous and useless) at a lower level of nuclear force, we have to conclude that science and technology advances have put us into a terrible predicament that we are too immature socially to handle. We have learned technologically how to destroy civilization in 1 hour—and we learned it before we learned how to live together on the same planet. No better example could be cited of the enormous inadequacy of the world's governmental machinery for responding to our increasingly technological society.

Let us consider one other example: information technology, the computer-communications revolution, a subject that other participants in this symposium address more fully.

Full application of advanced information technology can greatly improve productivity in industrial, business, professional, and governmental operations. All depend on information handling, and the new technology heightens by factors of thousands (sometimes millions) the capacity, speed, reliability, flexibility, and versatility of information acquisition, storage, processing, transmission, presentation, and utilization. Simultaneously, costs are radically reduced. It has been estimated that in the United States alone, if new technology were implemented wherever beneficial returns on the investment could be expected, expenditures of over a trillion dollars would be justified.

With this economic incentive, computer-communications implementations will be financed in all of the non-Communist world by private enterprise, to a high level. Despite the desirability of a maximum sponsorship from the private sector, however, a strong government role is absolutely essential in the democracies. Indeed, it is inevitable. The real challenge is to arrange for the government role to be conceived soundly and in a timely fashion.

The United States is particularly behind in evolving the most practical missions for the government and private sectors. No real updating of basic communications legislation, now a half-century old, has been accomplished in recognition of the enormous repercussions of the computer-communications technology breakthroughs of recent decades. The main government action has been in the courts of law.

Thus, the U.S. government, in unprecedentedly lengthy and expensive legal actions, sued both the American Telephone and Telegraph Company (AT&T) and the International Business Machines Corporation (IBM) as monopolies, although everyone even slightly sophisticated in the computer-communications field has known for years that computers (nominally IBM's field) and communications (nominally AT&T's field) were rapidly merging into one field, that the two big companies were thus destined to become each other's strongest competitors, and that, accordingly, neither could be properly considered a monopoly. The resulting court action broke up AT&T. Whether this was good for America or world society was never an issue. The action was solely in response to old U.S. laws designed for an isolated America and badly in need of revision to fit the present international, technological society.

Some industrialized democracies seem to have made more progress than the United States in establishing government-private relationships suitable to the computer-communications age. None, however, have yet risen to the full challenge of creatively exploring, selecting, and implementing the numerous missions that only national governments can encompass. Every industrialized country of substantial size is on its way toward the eventual installation of a domestic wideband computerized network of millions of terminals that receive and transmit voice, television, business data, teleconferencing, electronic mail, banking information, and signals in real time for control of transportation, production, and distribution. The system will be a complex of hardware, software, and information flow that dwarfs in size and power today's combined telephone, cable, and radio broadcast networks. Only the national government can set up policies and regulations to ensure privacy, guard against fraud, prevent monopolies in hardware and software, guarantee fairness in access to the network, control privilege and quality in injecting information, set standards for expressing information in electronics form to deter the creation of an electronic Tower of Babel, pass rules to determine liabilities, and assign geographical areas of activity. Since numerous elements of the productive structure of the nation are tied together by the computerized network, inadvertent system faults, mishandling, or flawed connections can create national economic chaos.

No matter how well national governments may discharge their information technology tasks domestically, essential international responsibilities will add greatly to the role of the individual governments. Just as each nation will choose to control the privileges and means of implementation of electronic information flow within its borders, it will also have an interest in regulating the flow of information across its borders. This will require further international arrangements and compromises. Information, in many respects, is like a product in international trade. In other respects, however, information transit between nations transcends in national—and hence international—importance the movement of finished goods and raw materials. For instance, the use of "electronic money," i.e., financial fund commitments represented by electrical signals, will lead every nation that intends to control its money supply and its banks to monitor the flow of information across its borders. Or consider that in the highly computer-automated future, information flow within the domestic network of a nation will constitute the very heart blood of the workings of the national economy, involving as it will information that schedules and interconnects production's many stages. Will not any national government that insists on control of its economy (and the policing of privacy protection and fraud detection in accordance with its own definitions and standards) view production information flow between nations as requiring internationally negotiated agreements?

What is going to happen for sure is that the free enterprise system, operating on a worldwide basis, will cleverly and legally maneuver around many of the inactions and ineptitudes of all governments. For instance, if the governments stand in the way of technology transfer between international units of a given company and if that transfer is seen as right, proper, and profitable, then some unanticipated legal way will be invented to transfer it anyway. The governments will be much in the act even if they lack settled policies and strategies. They will not totally halt free enterprise, but they will handicap it, particularly in that hybrid of free enterprise and governmental control known as the United States.

The summary of it all is that present governmental structures—those systems of deciding things, selecting priorities, and informing the public about policy alternatives—are too slow and inadequate. They are unsuited to the technological society. The United States, what with our "selfish interest constituencies' outshouting contest" type of democracy, may excel in creating handicaps. This may help other industrialized democracies in the world technology Olympics run off with medals. However, all countries will have trouble matching technology advance with appropriate social-political progress. Certainly, the Soviet Union does not appear to have a chance of going anywhere in the commercial products international trade contest, given the Soviet Union's paralyzing and demotivating bureaucracy and its priorities on military developments.

China may have a much better chance of forming a sensible relationship between technology opportunities and government actions. Its resources might be developed and its people might be employed to produce mass quantities of lower technology products. To do that, of course, China will need a stronger infrastructure—everything from more electric power to basic transportation and communications—for which the United States might become a strong provider of equipment and know-how. What the government's policies are might never become precisely clear, but the trade will occur because it will be advantageous to both nations.

More generally, around the world, technology advances might so badly outstrip governmental ability to act on big issues that the governments will settle down to only one mission. They will simply pass laws banning specific private actions, particularly those involving the crossing of borders by products, money, and information. More than ever, we would then see adversarial relationships growing between governments and private sectors. Rather than lead and be real participants in strategy, governments may merely try to minimize the most severe perceived negatives that result from a system ill-matched to technology advances.

Perhaps, by now, you feel I am being too optimistic, so I hasten to say that I do not think that what I am describing is all good. We can't halt technology advances. We need instead to increase social advances. We must innovate in governmental policy-making. This will require greater understanding by a large fraction of the public. In the United States, it is the rule that things have to get worse before they can get better; that is, most of the citizenry have to learn that things are not right and must be changed. The voters are already beginning to sense that about the nuclear weapons race, for example, but they have not caught up with many other social issues that are technology related.

You can see now why I am optimistic: things have to get worse before they get better, and look at how well we're doing on that essential first step!

Telecommunications

Ian M. Ross

An examination of the influence of technology on foreign relations must necessarily include telecommunications. All aspects of society have been influenced by the dramatic changes in the way people and, more recently, machines communicate. Communication is clearly a key element of infrastructure.

This paper reviews present and future capabilities of telecommunications as well as some of the key underlying technologies. It also suggests future applications of telecommunications that hold the potential for even more dramatic changes in society. Individual forces will, of course, play a strong role in determining which of these applications are actually realized. However, the long-term planning horizon of foreign relations requires an awareness of these applications along with the issues that they suggest.

The technology underlying telecommunications pervades many industries and much commerce. It has, for example, been applied to many fields, such as computers, aerospace, and national defense. The emphasis in this paper, however, is on the telecommunications network—that collection of facilities that makes communications ubiquitous by permitting people and machines to be interconnected at times and in ways largely of their own choosing. Until January 1, 1984, the development of the telecommunications network in the United States was driven by the American Telephone and Telegraph Company (AT&T) and its affiliated companies, known collectively as the Bell System, which also operated in an informal partnership with thousands of independent telephone companies. Thus, the account presented here reflects primarily Bell System experiences. No attempt will be made to suggest the degree, if any, to which the breakup of the Bell System will influence the future development and deployment of telecommunications technology.

The next section reviews the service capabilities of telecommunications today and suggests, broadly, the steps that were taken to achieve those capabilities in the major elements of telephony: customer terminals, transmission, switching, and signaling. Next, the status and trends of some of the key technologies underlying telecommunications are assessed, that is, microelectronics, software, and photonics. That discussion is followed by an account of potential applications and their likely impact on human activities. The paper concludes with a discussion of some broad national and international issues raised by these advances in telecommunications.

TELECOMMUNICATIONS ELEMENTS AND CAPABILITIES

Overview

The term *telecommunications*—"communicating at a distance"—seems to have been first used when the International Telegraph Union at the Madrid Convention in 1932 changed its name to the International Telecommunications Union. The present ability to communicate at a distance is a direct outgrowth of telephony. From the beginning of commercial telephone service, three desires have motivated the quest for improved technology: the first was for one person to talk to another from any point to any other point, regardless of distance, the second was for affordable telephone service, and the third was for high quality and reliability, because these are ultimately key to making telecommunications or any service valuable.

The fundamental objective of Bell's "Grand System"*—to permit

*In 1877—1 year after the invention of the telephone—Alexander Graham Bell wrote: . . . "The telephone may be briefly described as an electrical contrivance for reproducing in distant places the tones and articulations of a speaker's voice, so that conversations can be carried on by word of mouth between persons in different rooms, in different streets, or in different towns . . . ."

He went on to say that

> it is conceivable that cables of telephone wires could be laid underground, or suspended overhead, communicating by branch wires with private dwellings,

any two customers to speak with each other regardless of their locations—faced two basic technological challenges: the need to conquer distance and the need to interconnect any arbitrary pair of subscribers efficiently. As a result of many discoveries and inventions, systematic integrated planning, and substantial investment, these challenges were more than met.

Bell's concept of the Grand System, as well as the concept of "one policy, one system, universal service" enunciated by Theodore Vail in 1908, guided the Bell System, including Bell Laboratories, throughout its formative years. When universal service was substantially achieved in the 1960s, specialized, or vertical,† services became an additional focus of attention. The information age we are currently entering is made possible largely by the technology developed for the telecommunications network. Past developments and current trends in each of the elements noted above play an important role in the services currently available or achievable in the network.

Reviewing what telephony involves and the services that today's telecommunications network makes possible will enhance appreciation of the current technology.

For purposes of this discussion, telephony has four essential elements: *customer terminals*, which include the instruments that convert acoustic waves into electrical signals and vice versa; means for *transmission* of electrical signals from one terminal to another; arrangements for *switching* the connections between terminals; and methods for *signaling* between the terminals and the network to indicate that service is desired and to alert the called party.

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country houses, shops, manufactories, etc., uniting them through the main cable with a central office where the wires could be connected as desired, establishing direct connection between any two places in the city . . . . Not only so but I believe that, in the future, wires will unite the head offices of the Telephone Company in different cities, and a man in one part of the country may communicate by word of mouth with another in a distant place . . . . I will impress upon you all the advisability of keeping this end in view, that all present arrangements of the telephone may be eventually realized in this grand system.

†The term *vertical service* refers to any offering other than the provision of a single basic telephone on a customer's premises. The term embraces such diverse things as colored telephones, residence extensions, and call-waiting service.

Elements of Telephony

Call-Handling Functions

A brief review of the steps taken in setting up a telephone call will explain the role of the elements to be discussed in this section. Describing a call placed through a manual switchboard of a kind commonly used 50 or so years ago conveniently illustrates all of the necessary functions that must be accomplished in either manual or automatic systems.

To place a call, a customer lifted the receiver from the cradle of the telephone. This action operated a simple switch that completed a circuit from the central office to the telephone. It also lighted a lamp above an answering jack on an operator's switchboard, thereby notifying the operator that service was desired. The operator inserted a cord plug into the answering jack, which extinguished the lamp and connected the operator to the customer. The operator then asked the customer for the desired number, made a busy test, and connected to the called line through another cord plug. Depressing a key, the operator sent current to activate the ringer of the called party.

The operator's telephone was then disconnected and became available to handle another request for service. Supervisory lamps associated with each of the calling and called parties enabled the operator to determine when the called party answered and when either party hung up. The operator would then remove the cord plugs and break the connection. A customer needing operator assistance could rapidly depress the switch hook, causing a supervisory lamp to flash on the operator's switchboard.

When a call involved two central offices, the operator serving the calling party was connected to the one serving the called party over an interoffice circuit called a trunk.

Customer Terminals

The terminals that connect customers to the network are often referred to as customer premises equipment (CPE). Today, CPE embraces many types of terminals, including, for example, teletypewriters, data terminals, computer terminals, and, of course, telephones of many varieties.

The invention of the telephone showed the feasibility of a variableresistance, sound-controlled, battery-powered electrical circuit. Within a few years, additions to the basic elements of a telephone—particularly to the transmitter and the receiver—were invented. Since then, of course, the telephone has changed and improved dramatically.

In the early days of telephony, the basic need was to obtain higher volumes, by improving transmitter and receiver efficiencies. The next step was to make the speech sound more natural. These improvements required experiments to gain an understanding of the nature of speech and of the voice frequency responses of different types of transmitters and receivers. They also required the development of theories of electrical networks and tools and methods to measure not only the electrical responses of apparatus and circuits but also the subjective responses of listeners.

In 1951 the Bell System introduced a new basic telephone called the 500 set. The original design is still used today, with, of course, push buttons frequently replacing rotary dials. The availability of integrated circuits has led to more functions in the telephone: the Touch-a-Matic* telephone automatic dialer series, for example, permits one-button calling of selected numbers. Today, the market is crowded with telephones from many suppliers, telephones that have a great range of functionality and quality.

The forerunner of contemporary data terminals that transmit high-speed data over telephone lines was the page printer, introduced in 1912. Today, intelligent data terminals, with microcomputers for additional functionality, are commonplace.

The growth of digital computers in the 1950s led the Bell System to introduce Dataphone† data communications service in 1958. This service uses modulator-demodulator (modem) devices that convert digital computer signals to a form suitable for transmission over regular telephone lines and then reconvert them to their original form at the receiving end, a function comparable to the conversion of speech waves into electrical signals in the telephone. Today, hundreds of thousands of data terminals are used in the United States and throughout the world. In addition, computer and data terminals can be connected directly to digital transmission lines, described below.

Sophisticated computer terminals connected to the telecommunications network are now used extensively in businesses. In the future,

*Touch-a-Matic is a registered trademark of AT&T.
†Dataphone is a registered trademark of AT&T.

"teleterminals," combining the features of both computer terminals and telephones, will be used in the home as well as in business. One model is already available in a Florida trial, where AT&T and Knight-Ridder are offering Viewtron* service, a two-way home information system.

The variety of CPE is almost endless. Telephones include the familiar basic set, amplifying sets for the hearing impaired, coin telephones, hands-free phones, cordless phones, automatic dialers, and sets in a wide variety of colors, styles, and housings. In addition, there are terminals that transmit data and connect with computers, as noted above, and others that convert printed material into electrical signals. A significant trend is the inclusion of increasing intelligence in terminal equipment.

In summary, a wide variety of terminals has evolved. Progress has been driven by cheap electronic devices, including even microprocessors, which have given the terminals more logic and memory. The net result of all of this is a tremendous range of function for customers.

Transmission

The initial transmission challenge was to conquer distance to permit two-way voice communication between any two points. The first transmission medium was copper wire, which had previously been used for telegraphy. However, voice signals can be transmitted intelligibly only for short distances over copper wire. Initially, distance was extended by using improved materials, passive elements called loading coils, and mechanical amplifiers. By these means, usable circuits of 1,300 miles were obtained.

The breakthrough came with the 1907 invention of the Audion, the first vacuum tube amplifier. Vacuum tubes were incorporated in active amplifiers, called repeaters, for transcontinental U.S. telephone circuits and for wireless voice circuits linking Arlington, Virginia, with Paris, France, and Honolulu, Hawaii. By the end of 1915, the fundamental technical barrier to the problem of distance had been overcome.

The next challenge was to reduce cost by increasing the amount of information that the transmission medium could handle. Vacuum tubes also played an important role in the development of multiplexers, which combine a number of voice circuits for simultaneous trans-

*Viewtron is a registered trademark of the Viewdata Corporation of America.

mission over a common medium. These so-called carrier systems were widely deployed beginning in the 1920s.*

However, even with the art of electronics, copper wire has practical limits to the amount of information it can carry. Therefore, different transmission media were explored—coaxial cable, radio, and optical fibers. Today, coaxial cable systems carry about 30 percent of interstate telecommunications traffic. The latest system can carry 132,000 simultaneous conversations on a single cable. Coaxial cable has also been used for transoceanic circuits. The first such cable linking the United States and Europe, TAT-1, began service in 1956, after decades of work to develop highly reliable components. TAT-1 was retired in 1978, after handling 10 million calls without a single failure in any of its 102 vacuum tube amplifiers.

Radio circuits, of course, use the atmosphere, or free space, as a medium. Early systems operated at relatively low frequencies, which had rather moderate information-carrying capacity. By World War II, the ability to operate in the upper part of the radio frequency spectrum, known as the microwave region, had been achieved. The first commercial microwave systems were deployed in the early 1950s and now span the country. They have tremendous information-carrying capacity and form the backbone of the nationwide network. For example, a single system can carry 6,000 voice circuits or a dozen television channels.

At intermittent points along a route, microwave systems require relays that receive and then retransmit signals. These relays can be no more than 30–40 miles apart over level terrain because microwave signals travel in a line-of-sight manner.

Satellite systems also operate at microwave frequencies, but the relays are positioned in earth orbit. Thus, they can transmit signals over long distances and over terrain that would be inhospitable to ground-level systems. Satellites have supplemented cable systems for transoceanic routes, but they have not displaced cable systems and seem unlikely to do so.

The latest and most exciting transmission medium is the optical fiber used in lightwave systems. The use of optical fiber as a transmission medium was first postulated in the 1960s and developed rapidly for commercial application in the 1970s. Lightwave systems have

*Time-sharing has also been used to increase the number of calls in a transmission channel. Time assignment speech interpolation (TASI) takes advantage of naturally occurring gaps in the speech of any one talker in order to use these idle periods to assign another active talker to the voice channel. TASI has been used widely on transoceanic cables.

very high capacity, introduce extremely low loss levels into the transmitted signal, and have high immunity to electrical interference. Also, they are physically small and lightweight. Thus, they are currently being installed for use in many applications, such as communication networks in computers, in customer loops, in exchange trunks between central offices, and in the long-haul network. A lightwave transoceanic cable is currently under development for deployment in the late 1980s.

In addition to the type of medium, another important parameter of transmission systems is the type of modulation used to transport the information over or through the medium. There are two principal types: analog and digital. A telephone generates an analog electrical signal, so called because its amplitude and frequency correspond, one-to-one, to the acoustic waves of the voice signal. All early transmission systems were analog, and indeed most of the nationwide network was designed to handle such signals.

There are, however, significant advantages to transmitting signals in digital form, wherein electrical pulses represent the analog signals from which they are derived. The great advantage of digital over analog systems is that signal degradation is easier to overcome. Also, digital signals offer greater flexibility, since the pulses of one signal may be interleaved with those of another for multiplexing, and it makes no difference whether the pulses represent voice, video, or data.

Digital signals require a transmission medium with greater information-handling capacity than that of their analog counterparts, increasing cost. As electronic component costs have been reduced, however, the cost of digital transmission of voice signals has become competitive with that of analog transmission.

The principal coding method used today, pulse-code modulation (PCM), was invented in the mid-1930s. Limited use was made of PCM in World War II, with vacuum tubes, but the invention of the transistor in 1947 made digital systems commercially viable. The first commercial digital transmission system, T-1, went into service in 1962 and carried 24 voice channels on two pairs of wires in ordinary telephone cable. Its use spread rapidly, and today 70 percent of the circuit miles of cable in exchange trunks* use T-carrier.

Virtually all light wave systems are digital. Coaxial and microwave

*There are three aspects of transmission: one is between the customers and the central office (commonly called loop transmission, since it has traditionally involved loops of wires); the second is between central offices in an exchange area (the local or exchange networks); and the third is between exchange areas (the long-haul or national network).

systems may be either digital or analog. The proliferation of computers has caused more and more digital signals to enter the telecommunications network.

In summary, enormous increases in the information-carrying capacity of transmission systems have dramatically reduced the cost per circuit. Today, 50 percent of circuits are on microwave systems, which are gradually being converted from analog to digital. Although microwave technology still has tremendous promise, its application in dense areas, such as cities, may—because the technology uses radio—be limited by the availability of frequency spectrum. Coaxial cable systems carry many circuits, but this technology may have peaked because of the advent of lightwave communications.

Satellite systems are vulnerable to atmospheric effects, use the radio frequency spectrum inefficiently, and are relatively insecure. Thus, they are not expected to have as much impact on the future as lightwave systems, although they clearly have a role to play, particularly in broadcast as distinguished from point-to-point systems. Although modern electronics has greatly increased the capacity of loop systems using copper wires, the greatest impact in the future, as suggested already, will come from lightwave technology, which is already influencing loop as well as short-haul and long-haul transmission.

These systems collectively have brought down the cost of bandwidth, which means cheaper information-handling capabilities. They are all evolving toward a network driven by the decreasing cost of digital technology, a network that will meet any customer's needs over any distance.

Switching

The objective in switching is to interconnect customers efficiently. As the number of customers increases, the number of possible interconnections increases much more rapidly so that it is not feasible to run pairs of wires between every pair of subscribers. This problem was solved by the use of central offices to connect or switch loops to loops and loops to trunks. Loops connect customers to central offices, and circuits, called trunks, interconnect these offices. This general scheme is followed today.

As noted above, switching was originally accomplished by manually operated switchboards, which were gradually improved to mechanize more and more of the manual functions. The first mechanized switchboards were electromechanical machines that used a combination of electrically operated relays and wired logic. Thus, the logic that determined the functions and features that the machine could provide was inflexibly wired into the machine. Nonetheless, electromechanical machines were very competent and made possible the introduction in 1951 of customer direct distance dialing (DDD). By 1966, 90 percent of interexchange calls were dialed by customers. International DDD service began in 1970; in 1983 over half of international calls were dialed by customers.

The next major advance in switching came in 1965 with the introduction in central offices of the electronic switching system (ESS*), based on digital computer principles. The most significant advantage of ESS comes from the use of software control. This software, like the programs in digital computers, provides the instructions that tell the processor what to do. The processors that control electronic switches differ from general-purpose computers mainly in their much greater reliability. The software, combined with the computer-based power of the processors, permits a degree of intelligence and flexibility not possible with the wired logic in electromechanical switches.

ESS switches bring a whole new dimension of services to telecommunications. For example, one problem with electromechanical switches is their inability to switch the high data rates corresponding to digitized voice traffic. The latest ESS advance provides the ability to switch digital pulse streams directly, greatly simplifying the transmission-to-switching interface, saving costs, and simplifying operations. Although a capability to switch digits existed in the first ESS switches, the first system designed to switch in digital format was the 4ESS toll switch, which began service in 1976. This superswitch can now handle over 600,000 calls per hour.† Today, versatile, modular time division switches, which process signals in digital format, are economically attractive for exchange offices serving from 200 to 100,000 lines.

At this time, about 55 percent of former Bell System customers' lines are connected to electronic switches. These switches, with their software control, combine the logical versatility of digital computers and much of the flexibility of human operators. The network of electronic switching processors has an almost unlimited ability to serve

*ESS is a trademark of AT&T Technologies, Inc.

†It is important to note that the design of the 4ESS switch, as well as that of its predecessors, changes to incorporate technological advances. The 4ESS switch installed today occupies 25 percent of the space and consumes 30 percent of the power of the initial model.

customer needs, for example, to transport any information that can be carried by the transmission systems. Before discussing this ability, however, we must consider another essential element in telephony—signaling.

Signaling

A telephone system must have some means to provide and pass control signals to and from network elements and customers. Telephone users are familiar with signals like dial tone, busy tone, and ringing, but they are largely unaware of the many other supervisory signals and of the complexity and importance of the signaling network.

As noted above, in the days of manual switchboards, operators were summoned by lighted lamps when the customer wanted service. Operators then determined the number to be called and tested to see if a line was busy before completing the connection. With increased mechanization of the network, signaling became more complex, and many tasks previously performed by operators had to be done automatically. Dial pulses and, later, tones were used for signaling; these signals were transmitted over the same circuit used for conversation.

Increasingly, a separate, dedicated data network interconnects the electronic switching machines located throughout the nation and extends their call-handling functions. This network is called the common channel signaling (CCS) network. The CCS network has several major advantages. First, signals travel from processor to processor of the electronic switching machines in digital format and at very high speeds. This capability permits long-distance calls to be set up in as little as 2 seconds. Because the CCS network is separate from the network of voice paths, use of network capacity is more efficient, since these paths are not tied up when someone tries to call a busy number. Moreover, the CCS network permits access to central data bases and can carry much more information about calls than earlier signaling techniques could. Both of these features help make possible new types of information services.

The combination of CCS and software-controlled switches produces a network of great capability and flexibility. It permits the establishment of customized networks by making only software modifications. It also permits a variety of other specialized services. Some examples of these will suggest the prodigious capabilities of the network.

Specialized Services

In the earlier phases of telecommunications, service objectives were well defined. The operational and technical limits of existing technologies were also known, making possible clear definition of development challenges. As we enter the information age, however, the situation is reversed, in a sense. Although developments to reduce the costs, to improve quality, and to extend the range of services will continue, the industry faces a richness of technology. The functions, capabilities, and features possible are so great that the services provided by the telecommunications network will be limited largely by what the using public defines, wants, and is willing to pay for and what the government permits, rather than by what the technology will support. The services potentially available could change society as much as the industrial revolution did—hence, the frequent references to the information age revolution.

Voice Services

In the past, universal service in the United States meant making basic telephone service available at affordable rates in nearly all homes. By 1969 there were 90 residence lines per 100 households. Today, in addition to basic service, many specialized services satisfy a wide variety of user needs.

The electronic switches, and even some electromechanical systems with added software-controlled equipment, provide many custom calling services to exchange customers. These services include call waiting, call forwarding, speed calling (or abbreviated dialing), and three-way calling (for adding a third party to an established connection). Other service capabilities include recorded call answering on demand, custom announcements, and advanced calling, for message delivery at a specified time. Future features will permit screening of incoming calls for "selective call acceptance" or "universal do not disturb." Cellular mobile service provides regular telephone-grade service to an essentially unlimited number of mobile sets in a metropolitan area.

The network of electronic switches, including CCS and related data bases, as well as the transmission network, permits remote activation of the custom calling features noted above and many additional services. Capabilities available with this ESS network permit not only regular direct dialing, including international calls, but also customer-dialed credit card calls without operator participation. The ESS network has also made possible a single, nationwide number for national organizations and the selective routing of calls to a specified number, depending on the location of the calling party or the time of day. If the proper information is in a data base, personal locater service is possible.*

Data Services

Various digital communications services provide a variety of channel capacities, depending on customer needs, and are almost as ubiquitous as voice-grade telephone channels. For example, Dataphone data communications service is a private line service with rates of 2.4, 4.8, 9.6, and 64 (or 56) kilobits per second (Kb/s). It links more than 100 cities in the United States and connects to the Dataroute service in Canada. Various channel rates are provided to let the customer select the most economical service to meet his or her needs. For example, 2.4 Kb/s is useful for voice band data and for slow facsimile (minutes per page). Terminal-to-computer transmission at 4.8 Kb/s is suitable for retail stores placing orders with a wholesale house, for inventory control and sales audits by nationwide chains, for data entry from a remote terminal, or for communications between home computers. Higher capacity, 9.6 Kb/s, is suitable for use by multipoint systems (such as those that trucking firms use to arrange pickup and delivery), for electronic mail, and for interactive activities, such as point-of-sale credit verification and electronic funds transfer. Customers use 64 Kb/s for coordinating the outputs of factories, for centralized credit verification, for centralized credit card billing, for fast facsimile (seconds per page), and for freeze-frame video.

Another digital service, Accunet† T-1.5 service, can connect two locations with a 1.5-megabits-per-second (Mb/s) channel. The customer can change the mix of data and voice periodically according to the needs at a particular time. Accunet reserved 1.5 service is available for videoconferencing. Skynet‡ 1.5 service carries signals at 1.5 Mb/s

*The variety of the call-handling functions is impressive. More important, perhaps, is that they reintroduce a certain personal touch to telephony. In the old days, if a customer wanted to call John Smith, the operator might well have said, "He's at Joe Brown's. I'll ring him there." With call forwarding or with personal locater service, the equivalent can be done—if John remembers to tell the data base where he will be and when.

†Accunet is an unregistered service mark of AT&T.

‡Skynet is an unregistered service mark of AT&T.

or in combinations of several lower rates and is suitable for transmitting a mix of voice and data signals from one to several locations.

The network continues to be used to distribute radio and video programs to broadcast points. It continues to serve the news services and is increasingly being used to transmit newspaper copy to printing plants located around the country.

In the future, telecommunications will evolve toward extensive integrated services digital networks in the exchange areas and a similar national and worldwide digital service capability. These will integrate voice, data, and video signals for transmission and switching in digital format and for connection among any customers who have appropriate terminals.

UNDERLYING TECHNOLOGIES AND TRENDS

A brief review of the status of and trends in the technologies underlying potential new services is appropriate at this point.

Microelectronics

The first of these technologies is microelectronics—the world of tiny chips of semiconductor materials, principally silicon, containing a multitude of components through which electrons race to perform complex logical functions at high speeds. For over 20 years, the number of components that can be placed on a silicon chip has doubled every 12–18 months. Today, some individual chips contain over half a million components. One can soon expect over a million components, and by the end of this century, perhaps a billion.

Such densely packed chips not only perform increasingly complex logical tasks but also operate ever faster. Logic circuits of experimental devices today can switch in one ten-billionth (10^{-10}) of a second—about the time it takes a beam of light to travel only an inch and a half.

These increases in performance have been accompanied by dramatic reductions in cost. Today, the equivalent cost of a transistor is less than .01 cent—a thousandfold decrease in 20 years. (To put these achievements in another perspective, if similar progress had been made in aircraft design, planes carrying 500,000 passengers each would be flying between New York and London for a fare of 25 cents!)

Fundamental physical limits are not likely to retard microelectronics progress through this decade. Near-exponential growth will continue in the number of components per chip, and increases in operating speed will also continue, greatly increasing the processing capability of microelectronics and thus making possible a variety of new telecommunications and information services.

Lower cost has allowed microdevices to become very affordable and thus to be used ubiquitously throughout telecommunications. Such devices have increased the functionality of all of the products and systems in which they are used, and because of their size and low cost, those devices can be used anywhere they are needed or wanted—in terminals, transmission, or switching systems. In addition, it is important to note that microelectronics is driving the network to an all-digital capability. With the advancements in microelectronics still possible, we can anticipate much greater improvement in cost reduction and functionality.

Photonics

Photonics—or lightwave communications, as it is more commonly known—also underlies future telecommunications. In this technology, photons, the fundamental particles of light, are the information-bearing elements. Photons can be generated by lasers, routed by optical switches, and transmitted in hair-thin optical fibers. Compared with other transmission media, light wave communications systems have the advantages of broad bandwidth, which provides large information-handling capacities, immunity to electrical and electromagnetic interference, low signal loss, and small size and light weight. In its short history, the technology of fiber systems and short-wavelength, light-emitting diodes, lasers, and detectors has matured. Substantial progress has been made toward the next step, long-wavelength components. These developments are aimed at the two challenges facing optical systems: to transmit higher rates of information per fiber and to increase the spacing between repeaters.

The Japanese, British, and others, including many organizations in the United States, are active in photonics. The pace of progress is rapid indeed, and performance records do not stand for long. As of the fall of 1983, the transmission record was held by AT&T Bell Laboratories, where signals have been sent at a rate of 420 Mb/s over a distance of 162 kilometers without repeaters, and almost error free (an error rate of 5×10^{-10}).

To date, fibers have been used primarily in the exchange and national telecommunications networks. As fibers reach out toward end users, they permit the potential evolution from today's pervasive voice band and 64-Kb/s data channel into tomorrow's video-bandwidth channel. In addition, we will see an increasing integration of photonics and electronics through using lasers, photodetectors, and optical and electronic devices for logic.

In summation then, lightwave systems are becoming pervasive throughout telecommunications. We find this technology being used in short-haul and long-haul transmission and loop systems. Light wave systems are also linking up computer systems, bringing new capabilities right to the customer's premises and spreading out between switching centers in the local and nationwide networks to allow greater and more varied services. Soon, we will also have lightwave systems in our transoceanic cables.

Because of the rapid progress being made and the great potential remaining, lightwave technology is expected to dominate future transmission systems. The net effect of this is the increased availability of wide bandwidths and higher bit rates over any distance.

Software

A third major telecommunications technology, software, refers to the sets of instructions that tell the logic elements what action to take and when. Software determines what processors can and cannot do.

The telecommunications network has come to depend increasingly on software. Software is principally used in ESS. Today, the more than 3,000 ESS switches in the Bell and AT&T networks handle more than 50 percent of telephone traffic. All in all, the network and its supporting operations contain an embedded web of interconnected computers—the largest in the world—that operates with 40 million lines of computer code.

In addition, increasingly larger software programs are being required. For example, the switches used for both local and toll calls today each have 800,000 or more lines of code, and each large 4ESS toll switch has about 1.6 million lines. Even though the basic tasks of electronic switching machines are simple, the software challenge is complex because of the many overlapping transactions to be handled and the demand for great reliability.

During the busy hour of a large switching machine, something like 6 million real-time transactions take place, and at any instant some 100,000 program processes take place simultaneously. These machines, and the network they interconnect, must be highly reliable: lives depend on the reliability of telephone connections. The high degree of reliability in switching systems is achieved by a combination of redundant hardware and, as noted, large amounts of software. Of this software, much is used for fault location, diagnostics, and maintenance.

The benefits to be realized from advances in microelectronics depend heavily on software. Also, if we are to continue adding features and functions to the telecommunications network, we will need ever more complex software systems.

Although we have learned, painfully at times, how to produce complex software systems of high reliability, costs have been high. If we are to continue progress in software development while bringing costs down, fundamentally different ways of designing and developing software systems are needed. This is not a problem unique to telecommunications; it applies to all systems employing computers, and such systems are being rapidly deployed throughout our society.

POTENTIAL OF INFORMATION AGE CAPABILITIES

Microelectronics, photonics, and software are so rich that they hold the potential for a great variety of new services in both CPE and the network into which they have been incorporated through major accomplishments in systems engineering.

Highlighting a few such services might serve to illustrate this point, as well as to provide a general idea of the potential capabilities of the information age. These illustrative examples are not intended to be a view of the future, but are given instead to stimulate the thought of those not involved in telecommunications technology. In all instances, the emphasis is on the role of the telecommunications network—the vehicle that establishes connections between users (including those on the move) and information sources, that transmits information, and that permits manipulation of remotely located information. Today's technologies can have an impact on almost all normal social activities and interactions.

In education, for example, children confined to home can participate in classroom activities through audio and, in the future, video facilities. Audiences at remote and diverse locations can participate interactively in lectures through two-way audio/video connections. Individual learning courses, selected by students who can advance at their own pace, will be available at remote locations.

Broadband and interactive capabilities will permit individuals to share in many participative endeavors and games, thus extending the opportunities for entertainment.

Through telecommunications, health care professionals in one locale will be able to diagnose ailments of individuals in another locale; they will be able to provide expert advice from central to remote locations wherever needed. An entire hospital information system can be centrally coordinated, and signal-processing techniques can be applied to such advanced sensor-scanning devices as computerized axial tomography and nuclear magnetic resonance.

Selective access to specialized data bases can permit routine data searches from remote locations. In the United States today, several hundred data bases containing such diverse information as legal references, racing forms, and scientific abstracts are available to the public. Similarly, "tailored" newspapers are a possibility.

Extension of cellular mobile radio technology will increasingly permit communication with people in any location. Today's telephone number may become tomorrow's subscriber number, with the network programmed to deliver messages to locations of the subscriber's convenience.

Incorporating microprocessors in convenience appliances will permit their remote control via the telecommunications network and, as in the case of emergency alarms, automatic notification of the appropriate authorities.

Many changes have begun in business, trade, and industry, and others are possible. Banking and retail operations can be conveniently conducted from the home. Banks routinely exchange funds electronically. Electronic mail is currently being offered in this country. Teleconferencing, both audio and video, is becoming a substitute for travel. With appropriate data collection systems, firms will have timely access to market data. Inventory control will be improved, yielding significant economies; for example, networks already exist for sharing information on the location and availability of automobile models with particular features. Along with this will likely be a trend away from mass production to tailored products in many industries.

Similarly, national security will benefit from emerging technologies.* As in the past, the public-switched telecommunications network and specialized networks will provide new capabilities. In addi-

*No technology has been omitted from the discussion in "Underlying Technology and Trends" because of security classifications, although some applications have been omitted.

tion, microelectronics and photonics have found and will continue to find applications in military systems, just as analog and digital computers, microwave, signal processing, and other telecommunications technologies have in the past.

All of these illustrative applications have a common purpose: to provide users with the information they want, when they want it, and in the desired form. Potential applications are as numerous as the sources of information available in a society. Which applications emerge will depend on factors other than technology.

BROAD NATIONAL AND INTERNATIONAL ISSUES

This final section examines some broad issues that may be raised as a result of the technological developments in telecommunications and their possible national and international implications and impacts. These issues will be framed by first stating some assumptions about national and international objectives in which telecommunications can play an important role and then by making some observations relevant to policy directions.

It is in the United States' interest to help friendly developing countries.

Telecommunications technology can speed the advancement of developing countries. The United States should participate in providing such technology when it is in the national interest to do so. At the very least, such participation provides business opportunities for the private sector. However, policies regarding developing countries must reflect more than trade objectives, since there are also objectives based on social concerns and the desire to reduce international tensions.

Different countries, of course, have different needs, and the development of telecommunications in the United States is not necessarily a good model for other countries. The concept of universal service as implemented here may not be appropriate elsewhere. In some countries, direct-broadcast satellites with receive-only terminals in each home may serve a higher national priority than telephones in every residence.

Today, the opportunity exists to develop basic and specialized services together and in combinations that are most appropriate to the needs and desires of each country. Clearly established national and international telecommunications goals and objectives are vital to well-directed planning, engineering, and development.

The United States will continue to place high importance on maintaining a free and open society and will encourage other countries to do so.

Communications based on simple systems of telephones interconnected by copper wires could be effectively contained within national borders. Modern telecommunications, however, makes political boundaries essentially transparent.

This is not to say that political leaders are not trying, Canute-like, to stem the tide of free information flow that modern communication systems make possible. Transborder data flow restrictions, originally enacted in the name of personal privacy, are used to contain communications. Sophisticated jamming techniques are used to interfere with radio broadcast reception.

However, these efforts seem very limited in usefulness, since even more sophisticated methods can be used to overcome them. Thus, the trend for the future seems to be that members of the public will have available to them substantially the same information as their political leaders.

Telecommunications technology should continue to contribute positively to the international balance of trade.

A leadership role in telecommunications technology is a prerequisite to a strong international market position. Because of established relations between governments and their telecommunications industries, markets for telecommunications network equipment are among the most restricted in the world. Although the difficulties of penetrating the Japanese market have received the most public attention, similarly restricted markets exist in most developed countries with nationally owned telecommunications systems. A proliferation of technical standards for U.S. telecommunications products will restrict the international, and perhaps national, demand for the total range of products.

The pervasiveness of telecommunications technology may affect the trading positions of the United States vis à vis countries with which it shares its technology. We must be free to do business in other countries without having to surrender technology leadership. As part of an apparent trend, countries wishing to upgrade their telecommunications facilities require suppliers not only to manufacture in country but also to transfer their most modern technology to these countries. In some cases, the requirements to transfer technology go beyond the needs of the associated localities. This can be managed to some extent by introducing a time lag into the process of technology transfer, but this approach risks the loss of market opportunities if others are willing to trade long-term opportunities for short-term profits.

Thus, the tendency to require surrender of technology as a condition of market entry is developing into an issue that demands government attention.

Worldwide technical standards must be developed expeditiously and in a politically unbiased way.

Standards are critical to the evolution of the information age. New products must be compatible not only with one another but also with older products. The standards must be firm enough to ensure compatibility and prompt enough to ensure rapid introduction of new technology.

Within the United States, standards have been established largely without governmental intervention, primarily because the needs for such standards were evident in the evolution of an integrated telephone system. The setting of international standards, however, usually involves governmental intervention, since in many other countries the telecommunications provider is government owned. Moreover, standards negotiations require technical expertise that is often available only in the private sector; thus, close government-business cooperation is required. Various international organizations already exist—particularly, the International Telecommunications Union, headquartered in Geneva—to consider such questions. The technical issues that must be resolved include, for example, standards for integrating systems, assignment of orbital slots for satellites, and allocation of the frequency spectrum.

Since these discussions on international standards have often been highly politicized, a major challenge for the future will be to separate political from technical issues, enabling the technical issues to be resolved rapidly. The pace of technological change is such that rapid resolution is essential if society in general is to receive the maximum benefit from the technologies being developed. Also, the competitiveness of the United States in telecommunications requires that the United States have an effective voice in discussions on international standards.

The telecommunications industry will continue to support the national security and defense needs of the United States.

A position of technological leadership in telecommunications is essential to meet the national security and defense needs of the United States. For example, the underlying technology is vital not only for military and emergency preparedness *communications* but also for military *command* and *control* functions. This trio, commonly referred to as C^3, is at the heart of military effectiveness. This ubiquity of telecommunications technology underscores the need for international leadership. It also poses the difficulty of implementing an appropriate export policy for both technology and products.

The transfer of technology may affect national security and defense. What is important, however, is that the application of the technology and the performance of the product—not the technology itself—must be guarded.

The technology of the United States depends on a scientific base that will continue to thrive only in a relatively open society. Therefore, the ability of scientists to publish research results and to interact internationally with other researchers must be preserved. However, certain telecommunications products are critical to emergency preparedness and must be controlled. Between science and militarily critical products are technology and products that have potential for military application but that are also critical for foreign trade. It is essential that trade policy accommodate the sometimes opposing objectives of international competitiveness and military security in a way that provides clear guidance to the private sector. Telecommunications technology is capital-intensive both for research and development (R&D) and for manufacture. Global markets are increasingly required to justify these up-front expenses. Therefore, a clear and stable trade policy with appropriate export controls is ever more important for industry to continue to underwrite such expense.

Telecommunications services themselves are directly critical to national security. They link not only widely deployed military units but also governmental leaders. In addition, they are key elements in programs for verifying demilitarization and thus provide a mechanism for maintaining peace as well as military effectiveness.

It is important for the United States to retain a position of leadership in the sciences and technologies underlying telecommunications.

The United States must retain leadership in those telecommunications technologies that are important either to national security or to international competitiveness. This entails not only adequate R&D but also adequate mechanisms, such as manufacturing technologies, for converting the resulting science and technology base into competitive products and services. Unless governmental policies support such an objective, its achievement will be in jeopardy.

However, a policy of primacy does not preclude a policy of cooperation. Thus, there should be opportunities not only within the Western alliance, but also with developing countries to share in the development and use of new telecommunications technologies. Such cooperation might also be a tool for improving East-West relations.

Thus, it would seem that leadership in telecommunications is a useful adjunct of effective foreign relations, since the ultimate objective of both is to improve the quality of human existence.

It is essential that the intellectual property rights of U.S. nationals be adequately and effectively protected throughout the world.

Maintaining technological leadership requires adequate protection of intellectual property. Although most industrial countries have adequate legal protection systems, many countries have either ineffective systems or no systems at all. These latter countries have recently become centers of widespread product counterfeiting and illustrate that, worldwide, these systems must be strengthened.

Some developing countries have unfortunately taken the opposite track and have urged—through discussions on the proposed revisions to the Paris Convention for the Protection of Industrial Property—that existing systems be weakened. These same countries make it impossible to do business internally without surrendering valuable patent rights and proprietary information.

A challenge for foreign policy is to create an awareness of the value to these countries of adequate and effective intellectual property rights. Such rights are not, as they often suggest, an adjunct of colonialism, but rather are a mechanism for increasing the well-being of their own people.

In the short term, adequate systems will be likely only on a country-by-country basis, with minimum levels of protection established by bilateral or multilateral treaties. Regional systems, such as the one in the European community, probably represent the next logical development. Although worldwide systems represent a potential long-term goal, they are not likely for many decades.

CONCLUSIONS

The intent of this paper has been to provide an understanding of the technologies and services now available in the telecommunications network in the United States. The paper also touches on some of the international implications that are bound to have major impacts on our foreign relations as these technologies and services advance and grow in use throughout the world.

Communications has always been a major force in human affairs, influencing economic, social, and political activity and serving many human needs and desires. Like all other technologies, telecommunications reflects and amplifies humanity's strengths and weaknesses. Today, it presents enormous opportunities for constructive change, as forecast by this paper and the numerous writings today on the information age, but if these opportunities are to be fully grasped and their potentials realized, much work remains. The technologies must continue to advance, supported by considerable R&D; innovation must be allowed to flourish in a healthy, competitive environment; and, as noted previously, industries and governments must work together to see that the necessary standards are set to facilitate the proper linkage of the various systems nationally and internationally.

All of these are difficult tasks that require cooperation, an understanding of the technologies, and a vision of the future. The United States must exercise leadership in these tasks as in the other major technological endeavors that are reshaping our society and the world. The extent to which we do so will determine the shape of our future for generations.

Computer Sector Profile

J. Fred Bucy

ANY SECTORAL ANALYSIS of the computer industry must recognize the problem of definition. It is universally agreed that computers are a means to innovation in virtually all undertakings, but there is less unanimity on exactly what is meant by the term *computer*.

In the early 1960s a computer was perceived as a stand-alone mainframe unit (such as the International Business Machines [IBM] model 650) weighing several tons that was housed in a large, specially constructed area. Its operation required a team of experts. In the early 1970s, however, it became possible to place all of the logic and memory of a computer on a single chip of silicon approximately 0.25-inch square. The advent of single-chip microprocessors and microcomputers made it possible to incorporate the computing power of a mainframe into such products as microwave oven controls and handheld calculators. Today, a computer is often thought of as a relatively inexpensive machine that can be used in any number of activities, such as education, household data storage, increased job productivity, or entertainment. Its computing power can be 500 to 1,000 times that of an early mainframe (Table 1). Thus, a computer encompasses a range of devices from supercomputers, which cost millions of dollars and are used for such things as sophisticated weather forecasting, to an increasingly prevalent tool located in the home and on the job, to embedded microprocessors (such as those found in home appliances and automobiles) that are hardly recognizable to the user as computers.

TABLE 1 What Is a Computer?

Computer	Components	Power (Kilovolt-amperes)	Volume (Cubic Feet)	Weight (Pounds)	Air Conditioning (Tons)	Operation	Execution Time (Milliseconds) Add	Multiply	Transfer	Price
International Business Machines model 650	2,000 tubes	17.7	270	5,650	5–10	Stored program, magnetic drum with 2,000 words	0.75	20.0	0.5	$200,000 (1955 dollars)
Advanced scientific calculator	166,500 transistors	0.00018	0.017	0.67	None	Program steps, 160–960; memory locations, 100–0; stored program per module, 5,000 bytes	0.070	4.0	0.4	$299.95 (1977 dollars)
Texas Instruments professional computer	1,000,000 transistors	0.06	2.1	53	None	368,640 bytes, 184,320 words	0.008	0.0236	0.008[a] 0.0016[b]	$2,200 (1984 dollars)

[a]Memory to workspace.
[b]Memory to memory.
Source: Texas Instruments.

In this paper, the term *computer* will refer to an electronic device that accepts, stores, retrieves, and processes data according to programmed instructions. The structural elements of a computer include hardware—the basic processing unit and any peripheral devices, such as a keyboard (or other input medium), modem, mass storage, or printer (or other output medium)—and software, which gives the computer its instructions.

The difficulty in defining a computer makes it equally difficult to isolate a *computer sector* of the economy for analysis. Computers, whether for general or specialized use, are found in all aspects of economic activity, and any statements concerning the computer sector must be made with extreme caution to avoid the dangers of oversimplification and distortion.

The first section of this paper will trace the developments in electronics technology that have led to the current state of computer hardware and software capabilities and will attempt to forecast technical advances affecting computers over the next 10–15 years. The second section will describe the potential impact of computers in selected applications.

Because the ultimate use of computer technology will not be determined solely by an intrinsic technological drive, the third section will identify the major governmental policies (economic, social, and political) that have in the past either facilitated or impeded advancements in and diffusion of microelectronics and computer technology and products or are likely to do so in the future.

TECHNOLOGY DEVELOPMENTS AND TRENDS

Hardware

Approximately 4 decades have passed since John von Neumann proposed in 1945 the first stored-program digital electronic computer containing both data and instructions in the same memory. Since that time, the technology of digital computers has undergone at least three significant changes. In the late 1940s, computers were based on vacuum tubes. In the late 1950s, there was a general shift to transistors. This was followed by the appearance of integrated circuits in computers in the 1960s (Figure 1).

In the first 15 years after the invention of the integrated circuit in 1958, the number of transistors that could be placed on a single chip doubled every year. In the past few years, this rate has slowed to dou-

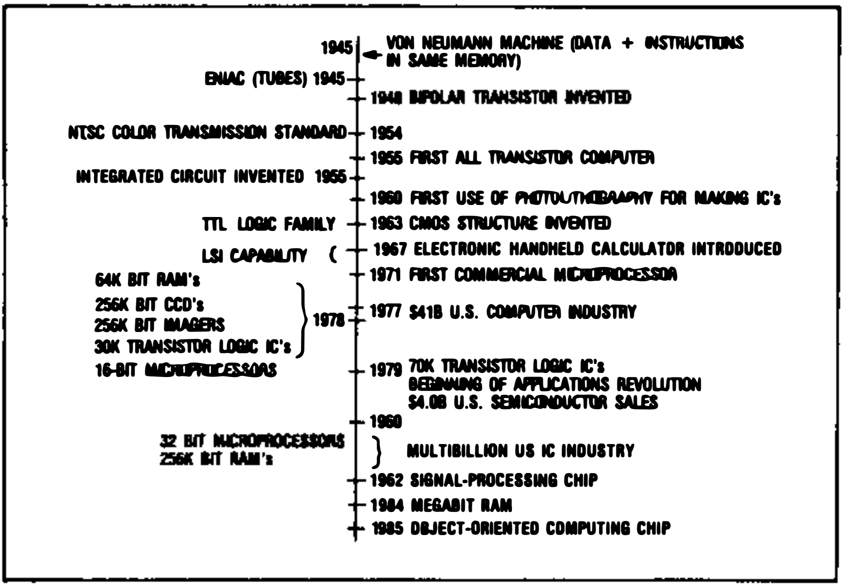

FIGURE 1. Evolution in technology. (Source: *IEEE Journal of Solid-State Circuits* and Texas Instruments.)

bling every 18–24 months. Twenty-four years of technology advances have produced four generations of chips of increasing device complexity: discrete components, containing one active element group (AEG)* per chip; small-scale and medium-scale integration, with up to 1,000 AEGs per chip; and large-scale integration, with up to 100,000 AEGs per chip. In the mid-1980s, VLSI (very-large-scale integration) technology is expected to put 1 million AEGs on a single chip (Figure 2) (Meindl, 1984). At the same time, the cost per AEG has been reduced by several orders of magnitude since 1960. This trend will continue through the VLSI era (Figure 3).

Computer memories, in particular, have undergone considerable change in the past 40 years. The memories in the original vacuum tube computers required one tube per digit stored. Later computers used mercury-filled acoustic delay lines and magnetic drums. More recently, computers relied on magnetic cores for rapid-access memory. Today, memory technology has advanced to bipolar and metal-oxide semiconductor circuits (Martino, 1972). These successive stages in the

*The lowest level of electronic circuitry, e.g., one logic gate or one bit of active memory.

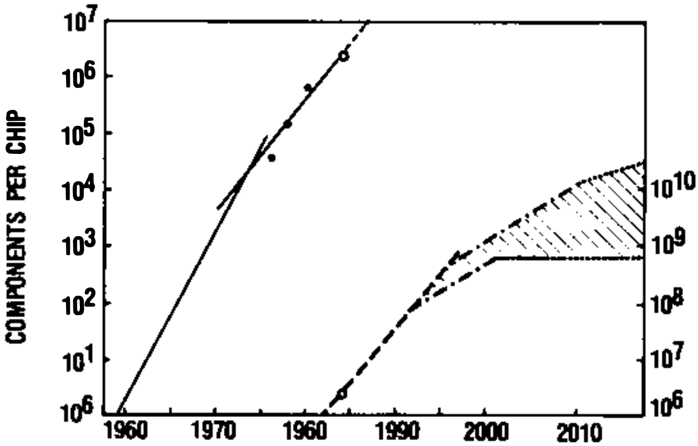

FIGURE 2. Integrated circuit complexity. (Source: Meindl, 1984.)

development of computer technology have increased the speed of computer operation and provided the ability to package more computational power and data storage in the same volume. The historical trend line in Figure 4 shows that by the late 1970s it was possible to purchase 100 times the computing power of a 1950s mainframe computer at roughly the same cost. For minicomputers, the cost decline has been quite dramatic.

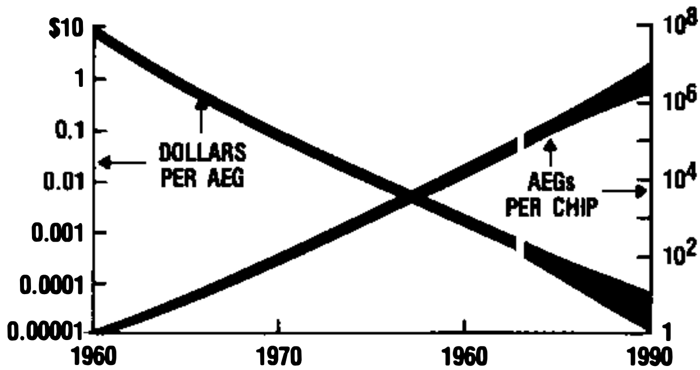

FIGURE 3. Lower user cost through greater product complexity. (Source: Texas Instruments.)

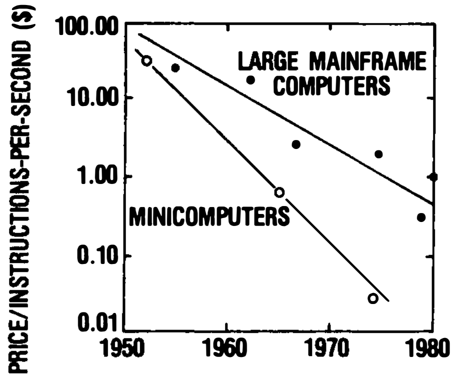

FIGURE 4. Historical trend in computer systems. (Source: Proceedings of the IEEE and Texas Instruments.)

Significantly, these increases in the functional capability of computers have followed a steady and predictable trend—a trend seemingly unaffected by the radical changes in technology that have occurred since 1945. Figure 5, which plots the ratio of memory size to access time versus the date of introduction of the computer, shows that progress has occurred at a steady rate despite the introduction of different technical approaches (see Figure 1) to the same problem (Martino, 1972).

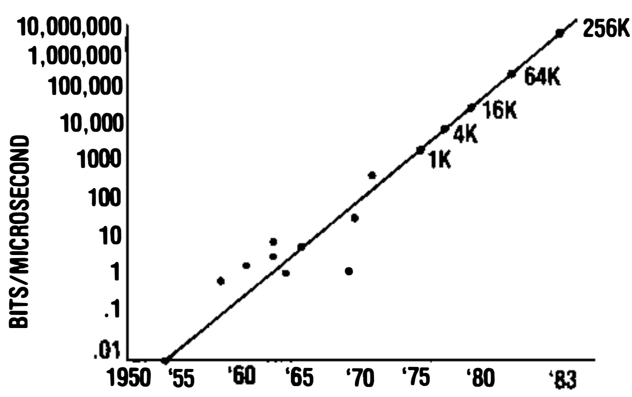

FIGURE 5. Bits per microsecond for computer memory components. (Source: Robert V. Ayres in *Technology Forecasting for Decision Making* and Texas Instruments.)

It can be inferred that advances in the technical capability of computer memory are largely independent of the technology used to create that memory. That is, even though we may be approaching the limits of silicon technology, it is possible to predict the availability of 1-, 4-, 16-, and 64-megabit memory chips before the turn of the next century, even if we cannot forecast the particular technology or technological breakthroughs that will lead to the development of these chips (Martino, 1972). Clearly, the ability to meet the demands of the expanding knowledge industry over the remainder of this century will not be limited by memory performance. Similarly, the historic exponential increase in the number of logic gates on a chip will continue for at least the next few years, leading to logic chips with several million transistors by the late 1980s (Jones et al., 1982).

The effect of these advances in computer hardware on the commercial world has been to open a vast market of small businesses and individual professionals that had never been able to afford the computing power of a mainframe and to move the computer out of special air-conditioned rooms and onto the desks of individual users. Similar advances in software are rapidly taking over the role once performed by a team of computer experts, allowing individual users with little or no computer training to make use of data-processing capabilities that were once the private preserve of large corporate data-processing departments.

In the consumer world, semiconductor technology has opened markets for computer applications that were impractical from a cost standpoint before the advent of the microprocessor. Since then, computers have found their way into average households in the form of handheld calculators, digital watches, computer-controlled cameras, appliance controls, video games, home computers, and preschool learning devices that reproduce human speech (Figure 6)—and these are but the tip of the application iceberg (Russo, 1980). As it becomes possible to put more and more transistors on a chip, microcomputers will become ever more powerful: for example, they will have wider data paths, larger address spaces, and more comprehensive instruction sets, with attendant increases in functional capability (Jones et al., 1982).

Software

Continued expansion in the use of computers is dependent upon the ability to conceive and develop new software that can fully utilize the

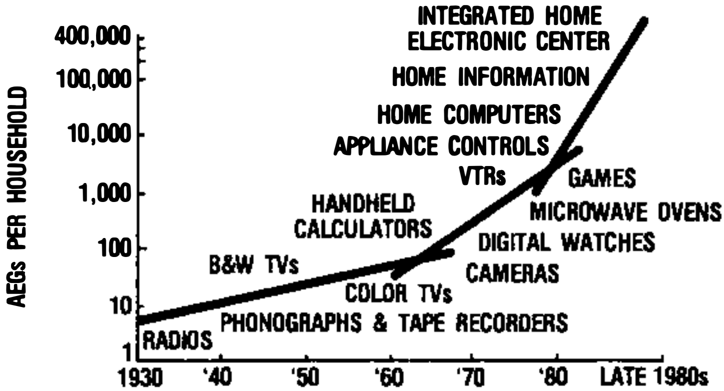

FIGURE 6. Increase of AEGs in the average U.S. home. (Source: Texas Instruments.)

capabilities of the hardware being developed. But so far, at least, software development has not matched the steady performance and cost improvements in hardware over the past 3 decades.

Essentially, the history of the evolution of software has comprised a number of attempts to "educate" the computer so that commands can be phrased in human terms of communication and internally transferred to machine levels of communication for execution. Of course, a reverse translation of the output, from machine language to the human level, has to occur if the results are to be meaningful.

Several interrelated reasons can be cited for the failure of software productivity and performance to keep pace with hardware. Over the past 30 years, programming has borne at least as much resemblance to art as to science; that is, although a number of methodologies exist for writing software, no single methodology has been established that is effective for developing many different types of software. Because of these limitations, software products (until very recently) have had to be custom-tailored for specific applications on specific pieces of hardware. Accordingly, software costs have not benefited from the experience-curve effect that has driven down hardware costs so dramatically.

In the commercial sector, software designers can now save time by reusing proven, already debugged routines on modular and portable software. Specific applications packages, once developed, enable an increasing number of users to solve their problems without having to program the computer. The more times a program is executed without modification, the greater is the productivity of the original design team. Specific examples of these phenomena are the use of spread sheets, text processing, data base management, and graphics software packages on professional and home computers. Software development is in the process of evolving from its present skilled-craftsman service context toward an industry that offers well-defined, competitively produced commodities.

In the military sector, the cost of developing software in 1970 was roughly 50 percent of the hardware cost. By 1985, software development costs are expected to exceed the cost of U.S. Department of Defense (DOD) computer hardware (Jones et al., 1982). The size and complexity of military software systems, their long development time (the software for one of the newest radar systems for U.S. Navy cruisers took nearly 16 years to develop), and their limited applications presuppose custom development and an almost constant need for upgrading and maintenance.

A number of techniques have been used by DOD in an attempt to solve this logistics problem. One of these, the Ada* project, is an effort to design a common language for programming large-scale and real-time systems covering a wide range of applications. The Ada program includes both the development of the language and the development of a programming support environment. Since the goals of the defense and commercial sectors are the same—i.e., program reliability and maintainability, concern for programming as a human activity, and efficiency—concepts and techniques developed in Ada have potential commercial application.

Another DOD initiative announced in 1983, Software Technology for Adaptable Reliable Systems, will address a wide variety of issues in the technology, human resources, and business aspects of computer software development that may also be applicable to the commercial sector.

A common problem in both DOD and commercial developments is the difficulty in determining software errors in a timely fashion. Figure 7 shows that as a software project proceeds to later stages of development, the range of costs to correct an error increases sharply.

One further step in software development is that of *artificial intelligence* (AI), a term first used in 1956. The capabilities of AI systems extend beyond numerical calculations and information retrieval by

*Ada is a trademark of DOD.

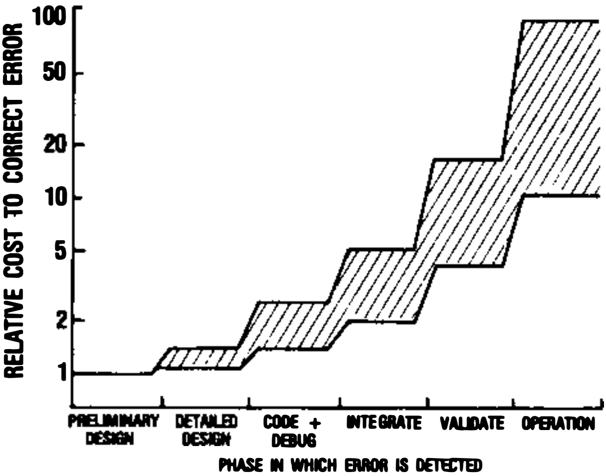

FIGURE 7. The cost of catching software errors late. (Source: DSMC *Concepts*.)

processing nonnumeric data, such as sentences, symbols, speech, graphics, and images. AI systems, with their expanded use of computational and storage capacities, were once a phenomenon found only in laboratories that had huge computers. With the rapid advances in solid-state microelectronics discussed above however, AI systems have become available for commercial use.

The central goals of AI have been to make computers more intelligent (i.e., to act more like humans) and to understand the principles that underlie human intelligence. AI deals with problems in such areas as game playing, theorem proving, general problem solving, perception (speech and vision), natural language understanding, and expert problem solving. Traditional computer programs are deterministic; that is, all inputs to a problem must be entered before a program will run. A single answer will result from this input. AI systems are not deterministic and are far more applicable to "real world" situations because answers to a problem (with a range of possible alternatives) can be based on partial information.

Expert system programs perform tasks that require a large body of stored knowledge; these tasks include medical diagnosis, chemical structure analysis, computer system configuration, and mineral prospecting. A latent demand exists for these types of programs because of the shortage of qualified human experts and because, unlike human beings, the expert systems can be easily replicated. Further, as new knowledge is acquired, it can be added to the existing expert system.

The symbiotic relationship between microelectronics and AI has been politically recognized in Japan, where, in 1982, a research project for the fifth-generation computer system was initiated and the Institute for New Generation Computer Technology was formed. The initial research goals of the project are to investigate architectures suitable for logical inference and data base operations (particularly, parallel architectures that can achieve extremely high performances), design a logic programming language suitable for knowledge representation and inferencing, and design a workstation containing a sequential inference machine.

Although the potential applications of AI are numerous and exciting, much work remains to be done in refining the generic rules of logic (i.e., how the human mind learns and reasons) and in transferring this knowledge to the computer system for each field of application.

The Data Explosion

The value of a computer lies in its ability to accept, store, retrieve, and process data. The essence of the "computer revolution" lies in the distribution of this computing capability to millions of individual users. In solving the problem of the individual's ability to acquire data, however, new problems have been created.

The growth in the availability of raw data places a premium on more efficient organization of data bases and on the development of software that will allow users to extract information from these data. It also raises a host of political issues related to the flow of information outside national boundaries, the individual's right to privacy, the security of data stored in computers, and the concept of information as a commodity with intrinsic value. These issues will be discussed in more detail below. Full treatment of the telecommunications impact of computers is left to another author in this book.

Technical Skills Requirements

There is a great deal of debate concerning the degree to which the skill levels in our society and the workplace will inhibit our ability to achieve the technological breakthroughs and attendant benefits of new computer technology. On one side of this debate are those who argue that America is facing an acute shortage of trained engineers and computer scientists that will perhaps permanently cripple our rate of technological innovation and place us at a serious competitive disadvantage in the world marketplace. On the other side are those who argue that the spontaneous corrective mechanisms of our society are adequate in the long haul to meet these needs. Policy issues begin to surface when the discussion turns to the gap between supply and demand.

A number of activities that are under way should increase the number of engineers. Entry-level salaries in the business sector are rising, trained individuals are being used more efficiently, retraining and continuing education are expanding, productivity-enhancing investments are increasing, second careers and part-time jobs are filling some teaching and engineering gaps, and enrollments in science and engineering programs are increasing.

However, the inadequate level of math and science training in the nation's high schools, the current and projected lack of qualified engineering faculty, and the lack of technologically up-to-date training equipment remain problems. Recognition of these problems by American industry and efforts to help alleviate them by allowing qualified employees to teach courses at all levels of education, by supplying state-of-the-art equipment, and by supplementing faculty salaries and student assistantships should help reduce the engineering gap.

The Technology Outlook

One way to view the past from our present vantage point is to propose three coexistent levels (or waves) of evolution that capture the broad outline of computer history. The first of these waves started around 1940 and focused on engineering efforts to build computers that could perform complex calculations not possible by other means. The second of these waves started in the early 1960s and focused on machine productivity, e.g., the IBM 360 family. In this era, computers served the needs of large institutions. The last of these waves to date is the era of user-friendly computers. In this era the ability of individuals to cope rapidly with complex situations, or "people productivity," is the key factor. The following are some of the developments in computer technology and usage we can expect to see over the next decade:

• *Rapid Response* There will be an increased emphasis on techniques for efficiently using memory and structuring data bases so that rapid responses to inquiries can be achieved.

• *User Responsiveness* Computer architectures that take maximum advantage of the processing power inherent in VLSI technology will emerge and effectively support symbolic as well as numeric processing. One goal is to build architectures that can support several different high-level programming languages and that are more responsive to the specific needs of operating systems and software in general (Patterson and Sequin, 1980). A second goal focuses on high-end microprocessor applications. Parallel processing, or the application of several processors to a single task, would yield a large amount of work in a far shorter length of time than is now possible (Buzbee, 1983).

• *The Right Place at the Right Time* The variety of peripheral devices will rise to meet the continuing proliferation of specialized user needs. Small computers and large mainframes will rely increasingly on expanded communications to distribute computation and data, enhancing the ability of the systems to place the right amount of computing capability where needed.

• *Machine Interfaces with Machine* New technologies will connect a variety of electronic devices within a work area or a building, i.e., "local area networks," and may have a major impact upon the usage of computers. Local networks function by allowing different terminals, computers, and peripheral devices to talk efficiently to one another. One benefit of this concept is the greatly reduced cost of adapting the system by adding a new component, leading to greater flexibility and ultimately to improved quality and productivity in the work environment.

• *Human Interface with Machines* The era of "logic and memory plenty" will make it possible to build machines that adapt to the user instead of vice versa. Voice recognition, optical character recognition, programmable display push buttons, and touch-sensitive displays will provide alternatives to the keyboard for communicating with computers. "Natural language" systems are emerging that allow the user to ask questions of the computer in a familiar language, such as English, rather than in a computer programming language.

• *Software Development* Software will continue to be an increasingly important factor in the cost, effectiveness, and content of computer applications. Because software is emerging as a product in its own right, a virtual revolution in the techniques of producing and using applications software is on the horizon. Software will become more portable between systems because of operating system and language standardization efforts. The ability of users to specify what they want and to acquire it at an affordable price will grow. Also, new relationships between the producers and users of software will emerge.

In summary, the growth of performance at the engineering level of component technology appears to be inexorable into the foreseeable future. The same basic motivating force will exist as it did some 40 years ago, when computer development was initiated, i.e., the need to solve unique, highly complex problems by using large mainframe computers. Therefore, the tailoring of hardware and software to achieve optimum cost-benefit solutions to enterprise management, from multisite corporations to small businesses, will continue to develop. However, the most dramatic revolution is just beginning, that being the era of user-friendly computers and computers embedded in equipment operated by individuals. This latest wave will be driven by new concepts in the organization of software that will soon begin to influence significant changes in hardware. This will ultimately bring down the cost of computing power available throughout all segments of society.

POTENTIAL IMPACT OF COMPUTER APPLICATIONS

The microcomputer and microprocessor have dimensions and power requirements that make them applicable to almost any human activity. Consequently, almost all sectors of modern society are seriously considering how to perform traditional functions more efficiently through computer usage or how to perform functions formerly considered impossible. This section will discuss a few of the many areas where such change is under way.

Education and Training

Computer-aided education and instruction began in the 1960s, using mainframes with remote terminals at several installations. Since then, educators have been analyzing the electronic delivery of various aspects of the learning process. School administration has also benefited from the use of computers for a significant number of years.

Despite the potential benefits of computer usage in education, several problems have delayed the widespread introduction of microcomputers into the classroom. The first of these is cost. Although more than half of all schools in the country have at least one computer (Williams and McDonald, 1984), educational budgets are constrained. Computer usage cannot be spread across grades or within subjects.

A second problem is quality software. As discussed previously, software development in general has not advanced at the same pace as that of hardware, and many educational software packages (courseware) are little more than drill and practice routines. The real educational power of computers lies in their capacity to provide students with individualized instruction in an interactive mode. For example, some innovative software programs "can demonstrate abstract concepts in such areas as physics and math. They can allow a student to experiment with several solutions to a problem. . . . Simulations can be run in real time, permitting a student to observe a process repeatedly or see the effect of variations." (Ploch, 1984.) However, until more computers are available in the schools, many developers will not commit the necessary resources to develop this type of courseware.

A third problem is a lack of teacher familiarity with computer systems. This is being overcome as schools train their teachers to use computers to evaluate available software, integrate software with courses, and individualize or write software programs themselves to accommodate specific local needs.

Despite growing pains, the computer will become a necessary adjunct to the classroom during the next decade as the existence of computers at home and in the workplace reinforces computer evolution in the schools. Decreasing costs will enable rapidly improving student/computer ratios. Reliability and ruggedness of computers will continue to improve, and the packaging of computers will allow more portability and flexibility in their placement. The effectiveness of self-instruction, retraining, and continuing education will be enhanced. In addition, the use of embedded microprocessors in equipment will simplify operator interface, easing the training problem.

Another exciting area is the electronic delivery of job performance aids. Small portable devices will soon aid operators and maintainers to operate, troubleshoot, and repair complex equipment more effectively. The computer will also aid in simplifying the voluminous technical documentation that is now part of all complex equipment.

Wide disparities will exist in the rate of adoption of computers, depending upon geographic region and level of training. These disparities will exist for a significant time as the system responds to the multiple constraints and pressures brought about by changing events.

The Factory

In the late 1950s, experts predicted that within a decade single machines would control whole factories. Although this vision is yet to occur in its entirety, islands of automation in the manufacturing process have been established and will eventually be linked together to form total computer-integrated manufacturing (CIM) systems (Charlish, 1984).

The emergence of manufacturing automation has been due to "a few major technological developments in electronics in the past few years, especially the great reductions in cost and size of the computer memories. These developments have meant that highly complex systems can be built and programmed at reasonable cost and convenient size. Another key development has been numerical controls which, when allied with computers, turn machine tools and robots into highly flexible and easy-to-use instruments. . . . The new technologies offer the potential of turning any type of manufacturing into an automated process, even if production batches are quite small." (Rodger, 1984.) Key factors in manufacturing automation are quality and reliability.

The process of computerizing the factory began with production scheduling and the use of unmanned machine tools. Later, computer-aided design (CAD) emerged, in which design drawings could be constructed on a video screen, manipulated, updated, and stored electronically. Once these product dimensions had been defined, the concept was extended to computer-aided engineering (CAE), where "what if" methods of prototyping could be carried out on the screen, without having to experiment with actual material. The result has been better products designed more quickly and cost-effectively.

Another extension is computer-aided manufacturing, which uses the same collection of comprehensive information about the product as CAD and CAE to derive molds, die tools, and machining strategies. A further concept in manufacturing automation is that of flexible manufacturing systems (FMS), where production machines are linked by means of handling devices (such as robots) to transport systems and communications lines, with overall control by computer. At any moment the computer knows exactly where each component is and what is happening to it. The result is a reduction in lead time, work in progress, and direct labor—and more new products. So far, only about 100 FMS are in use worldwide (Kochan, 1984).

"The major challenge now, and the major opportunity for improved productivity, is in organizing, scheduling, and managing the total manufacturing enterprise, from product design to fabrication, distribution, and field service." (Gunn, 1982.) The final step in manufacturing automation, the linkage of islands of automation in a CIM system, is illustrated in Figure 8.

The Office

Because computer technology is primarily concerned with information, one of the greatest productivity impacts of computers is expected to be in the office, where white-collar workers spend 80–95 percent of their time communicating and managing information (Toong and Gupta, 1984). The office environment of the future will utilize

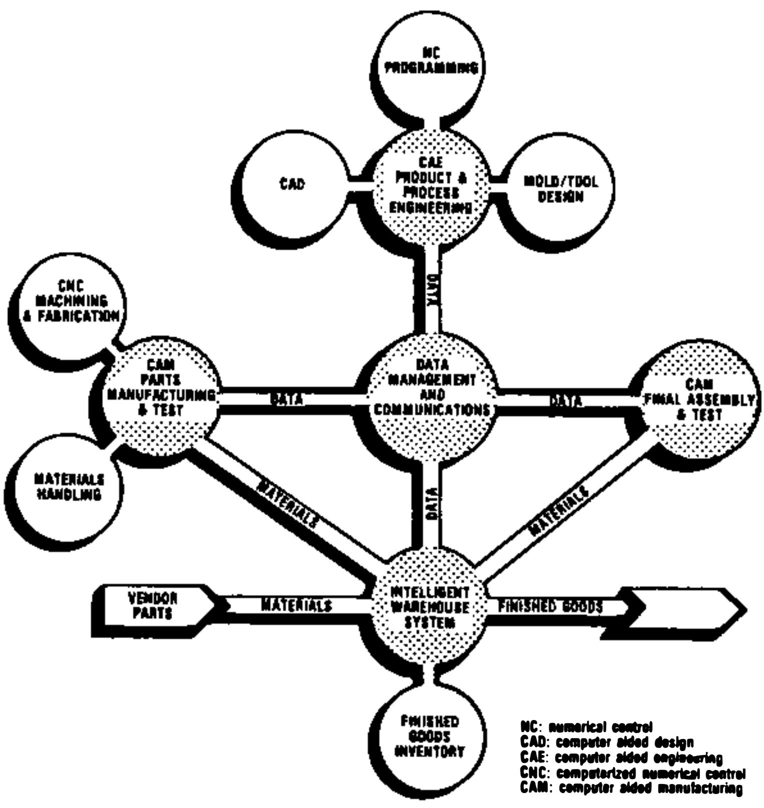

FIGURE 8. The production process of the future. (Source: *Financial Times*.)

powerful, knowledge-intensive personal computation within a network of cooperating computers and their users. A major increase in productivity will result from the ability to access large data bases containing information appropriate to the specific job function and from doing so in an interactive query mode, performing what-if analyses, and integrating data imagery with textual, numeric, and graphic representations. Electronic mail, including facsimile, will increase the ability to communicate, as will electronic conferencing. Electronic filing will reduce the time required to file and retrieve documents and will greatly increase the storage capacity necessary for such information while reducing space. Systems with text-reading and speech recognition capabilities will be developed. The overall increase in productivity resulting from these capabilities will have a major economic impact.

Agriculture

Computer usage in the agricultural sector has been limited to a few "innovators," even though a number of programs are available and potential applications are numerous. However, changing economic conditions and growing lender and landowner demands now necessitate more comprehensive financial statements and intensify the need for attention to the business management aspect of agriculture. Because of this new emphasis and the inherent ability of electronics technology to overcome the relative isolation of rural living, computer usage in agriculture is expected to become a recognized necessity in the next few years and to escalate rapidly thereafter.

Computer applications to agricultural needs include forward planning and control, monitoring of farm systems, accounting, financial analysis, and recordkeeping. Information needs that can be supplied by computer networking include futures prices; national, regional, and local market prices; international and national crop conditions; and market news. Specifically tailored local weather forecasts, storm warnings, and maps are possible computer applications, as is farm management information, such as extension service and co-op news, legislative updates, agronomy tips, and pest control advisories.

Current uses of microelectronics technology in agriculture include irrigation control through measurement of the level of moisture in the soil, measurement of moisture in grain silos and control of the drying fan and ration formulation for cattle. In late 1983, the Texas A&M

University System formally announced the start of a 3-year project to design and implement a fully computerized "farm of the year 2000," the primary objective of which is to develop and demonstrate a state-of-the-art computerized approach to operating and managing a commercial-sized farm. The purpose is to apply electronics technology to integrated production, finance, and marketing information systems and further integrate this with computerized monitoring and control of crop and livestock equipment and production facilities. This is the only project of its kind in existence, and it illustrates both the potential for computer usage in the agricultural sector and the development that remains to be done.

National Defense

The challenge facing the U.S. military is the fielding of affordable, effective, conventional and strategic deterrents to cover a wide range of scenarios. Computers and microelectronics are one of the major determinants of that capability and are growing in importance. When properly used, technology can assure that superior performance is achieved. There are a number of major systems in the field and in development where software determines total system performance. Software is the medium in which all interactions of the components of a vehicle are synthesized into a working system.

The military acquires much of its tactical advantage by positioning forces in the right place, at the right time, and in the numbers required. The command, control, communications, and intelligence functions necessary for this capability are dominated by electronics technology. For example, tactical data acquisition requires extremely sophisticated sensors that do not reveal the presence of the sensor or cannot be easily confused or countered. Precision terminal guidance of weapons enables the military to concentrate force and, when coupled with autonomous homing techniques, has become one of the linchpins of U.S. field supremacy. The dramatic reduction in the size and weight of microcircuits, plus their inherent ruggedness, has made this possible.

Although many of these military systems would be useful primarily in major confrontations between sophisticated armed forces, limited actions or peacekeeping operations benefit from computers and microelectronics, as well. For example, night vision devices and other surveillance techniques deny the opposition the ability to concentrate forces or achieve surprise at night. When coupled with these surveillance devices, improved communications greatly augment the effectiveness of small-arms fire and infantry tactics.

Any major battlefield of the future will be characterized by an increasing dependence on data flows and processing to convert that data into information. There will be more dispersed operations with a significantly reduced dependency on traditional support systems. These will be feasible only through the enhanced use of computers in analysis of requirements, concept formulation, design, manufacture, production, and support.

The Home

Perhaps because it is the area that will directly affect the greatest number of people, the "electronic home" of the future is a popular scenario for forecasters. Although many of the traditional functions in the home will be augmented by the use of computers (appliances, energy systems, security, smart telephones, home finance, shopping, and entertainment), these are only the more obvious applications. New approaches to education and work life in the home are beginning to surface, support for the aged and handicapped is now possible in ways not feasible a few years ago, and medical aid and diagnosis for the ill in the home offer new concepts of medical care. Improved access to information and data as a result of the combined effect of telecommunications and computers will create new opportunities for individuals to participate in economic and social activities while remaining at home.

The real driving force for change will be the individual scale of new computers, both in size and function. Ease of use will change the effectiveness of society in general, as well as its willingness to adapt.

Summary

The examples presented above demonstrate the growing and pervasive nature of the impact of computers and microelectronics on the activities of modern society. Other examples, such as health care, financial services, and the distribution of goods, would illustrate the same story. The evolutions under way are affecting the quality and efficiency with which society carries out its established functions, and new innovative functions are emerging. It should be emphasized that the impact of computers and microelectronics has been described from a U.S. point of view. The effects are therefore colored by levels of education, income, industrialization, and culture within this country. The levels and foci of impact on other cultures and nations will undoubtedly be different.

ISSUES AFFECTING THE RATE OF TECHNOLOGY ACCEPTANCE

An increase in computer usage can be predicted with certainty, because computers perform functions useful to society. However, the rate at which this usage expands is greatly influenced by economic, social, and political factors. In particular, technological change can be either facilitated or impeded by governments—either through direct support or, more frequently, through the creation of an environment of economic incentives or disincentives for new technological development.

It is beyond the scope of this paper to explore fully the many factors—both societal and governmental—that may affect the computer sector, but a number of important examples of such elements are noted below in the interest of completeness and because of their potential relevance to foreign policy considerations.

Employment

The issue that has generated the most debate regarding the acceptance and use of computers is the potential impact of computer usage on the labor force. Some analysts have predicted that computer usage will result in massive structural unemployment as workers are displaced by productivity-enhancing technology. Others look to high-technology industries to solve all of the economic ills of society.

No historical evidence supports the assumption or fear that enhanced productivity will result in sustained, high levels of national unemployment. Analysis of the impact of productivity on economic growth over the past 30 years demonstrates the opposite (Figure 9). An almost perfect correlation exists between productivity growth and real economic growth that is essential to the creation of jobs in the long term. (Although U.S. productivity growth is lowest in the 1950–1982 time frame, absolute productivity remains highest in the United States.) At the same time however, the implication that computer and microelectronics industries can make up the structural loss of employment and output suffered by the traditional industries is too extreme.

A recent Data Resources, Inc., study of industry growth patterns in

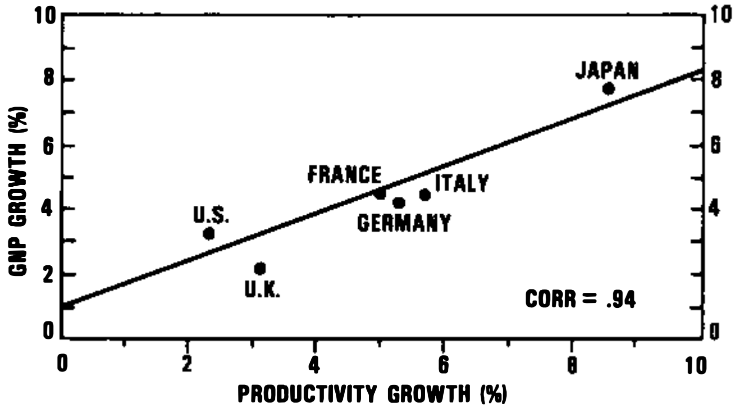

FIGURE 9. Productivity and gross national product growth, 1950–1982. (Source: Department of Commerce, International Economic Indicators.)

the next decade shows that constant-dollar output of high-technology industries is projected to grow to about 10 percent of the gross national product by 1993, an increase of 87 percent, more than double the 38 percent gain of manufacturing and almost twice as high as the 45 percent increase in the service sector (Figure 10). However, because the current output level of high-technology industries is small (only one-sixth that of manufacturing and one-ninth that of services [Figure 11]), its absolute dollar gain in output is also small (only one-third that of manufacturing and less than one-fourth that of services [Figure 12]).

Comparable growth rates for employment also favor high-technology industries (Figure 13). However, again, because of the small 1983 employment base, the absolute gains in high-technology employment during the decade are projected to be about 750,000—only one-third that of manufacturing, or one-twelfth the increase in the work force of service industries (Figure 14). Put another way, employment gains in the high-technology sector will be less than the 790,000 jobs lost since 1978 in the U.S. auto and steel industries alone.

Although they are performing significantly better in all areas of growth, the expected direct contributions of high-technology industries to output and employment are, in absolute terms, too small to displace traditional industries as spark plugs for U.S. economic growth. However, there are indirect contributions, and the absolute numbers of jobs lost in traditional industries versus jobs gained in the computer sector does not tell the whole employment story. First, the

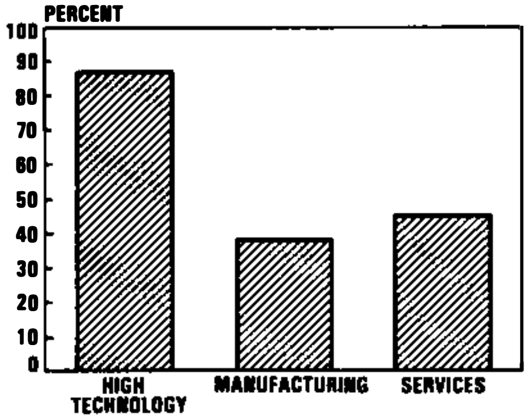

FIGURE 10. Forecast for output growth, 1983–1993, in constant 1972 dollars. (Source: Data Resources, Inc., in *Business Week*.)

high-technology sector can have a significant impact on employment through its multiplier effect on downstream activities. For example, estimates by the Department of Commerce show that during the decade of the 1970s, each new job in technology-intensive industries created six jobs in those sectors that were the end users of high-technology products and services. This ratio may be even larger in the future.

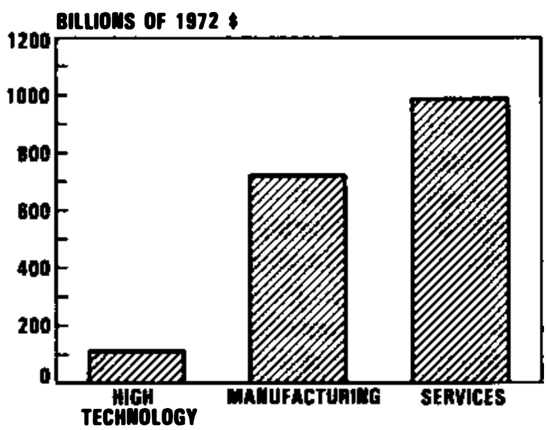

FIGURE 11. Output production in 1983. (Source: Data Resources, Inc., in *Business Week*.)

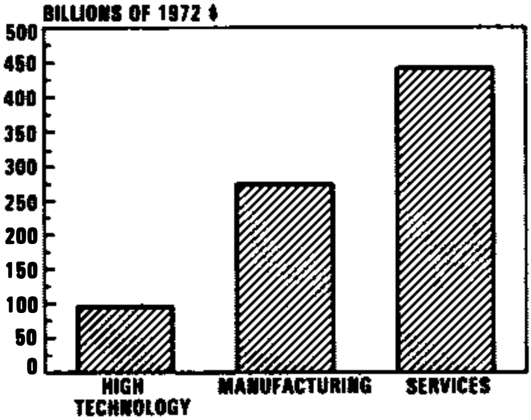

FIGURE 12. Forecast for output gains, 1983–1993. (Source: Data Resources, Inc., in *Business Week*.)

Second, the employment impact of computer technology extends even beyond the immediate range of producers and users of high-technology products. Computers in the form of robots, minicomputers, programmable controllers, and CAD systems can provide the means for manufacturing industries to recapture or increase their competitive positions in world markets.

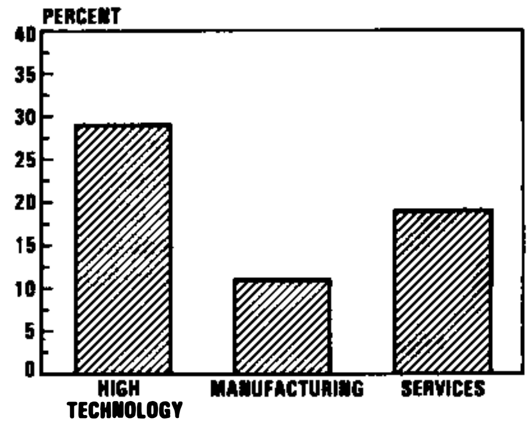

FIGURE 13. Forecast of employment growth, 1983–1993. (Source: Data Resources, Inc., in *Business Week*.)

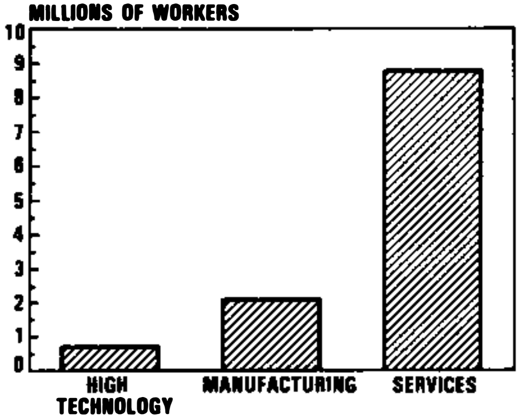

FIGURE 14. Forecast of new jobs created, 1983–1993. (Source: Data Resources, Inc., in *Business Week*.)

Finally, the impact of computers on the productivity of the service sector must be considered. It is the largest sector of the U.S. economy and historically has been immune to the productivity improvements that have occurred in the agricultural and goods-producing sectors. Lagging productivity in the service sector has been a significant factor in the stagnation of the U.S. economy in recent years. Productivity improvement through the use of computers can have a dramatic impact on economic growth.

Although the use of computers will result in short-term worker dislocation—a temporary mismatch between available jobs and workers' skills—computers can have a significant impact on real economic growth. The intensive use of computers and computer-based automation "over the next twenty years will make it possible to conserve about 10 percent of the labor that would have been required to produce the same bill of goods in the absence of increased automation. The impacts are specific to different types of work and will involve a significant increase in professionals as a proportion of the labor force and a steep decline in the relative number of clerical workers. Production workers can be expected to maintain their share of the labor force; direct displacement by specific items of automated equipment (like robots and numerically controlled machine tools) will be offset by the increased investment/demand for all sorts of capital goods, especially computers. A comparison of the future demand for labor with its projected supply suggests that the labor savings made possible by increased automation will not be so dramatic as to result in an overall labor surplus, at least not by the year 2000" (Leontief and Duchin, 1983).

However, if government fails to deal effectively with the short-term dislocation effects of computer usage, it may deprive the economy of the full value of computers in the longer term.

R&D Tax Incentives

An important government stimulus to technological innovation in the United States is the Economic Recovery Tax Act of 1981, which provided research and development (R&D) tax incentives: a corporate tax credit for increased R&D spending, a new capital cost recovery system for R&D equipment, and an increased deduction for manufacturers' donations of new R&D equipment to universities. Findings after approximately 2 years of experience are clearly provisional, but it appears that these tax incentives have encouraged firms to maintain growth in R&D spending despite the recession (*An Early Assessment, 1983*). The net result of such a government strategy as tax credits is that companies are able to fund more R&D while maintaining the same profit levels. An analysis of the various options available indicates that an even stronger R&D tax credit would demonstrate conclusively the positive impact of this approach.

Venture Capital

Small firms, unhampered by layers of management, make a disproportionately large contribution to innovation; thus, the rate of technological change is directly affected by the level of new capital flowing to fledgling companies. Another governmental method of stimulating technological advances has been to lower the capital gains tax on personal income and thus effect an increase in venture capital. Figure 15 documents the impact of capital gains tax rates on new capital committed to independent venture firms. Clearly visible in 1980–1982 is the phenomenal growth of funds for this purpose, 68 percent of which were targeted for the computer and microelectronics sectors (*Financial Times*, 1983).

Capital Investment

Government policies that influence the level of capital investment will strongly determine the ability of the computer and microelec-

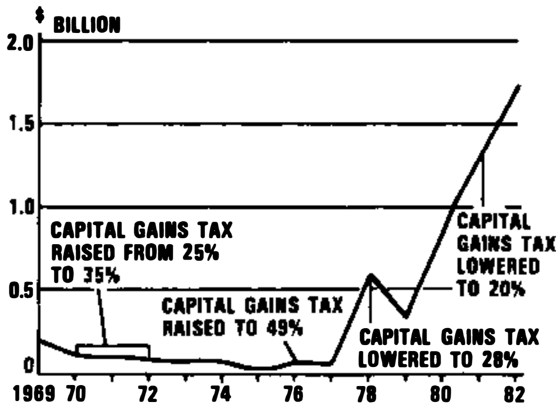

FIGURE 15. New private capital committed to independent venture firms. (Source: *Venture Economics*.)

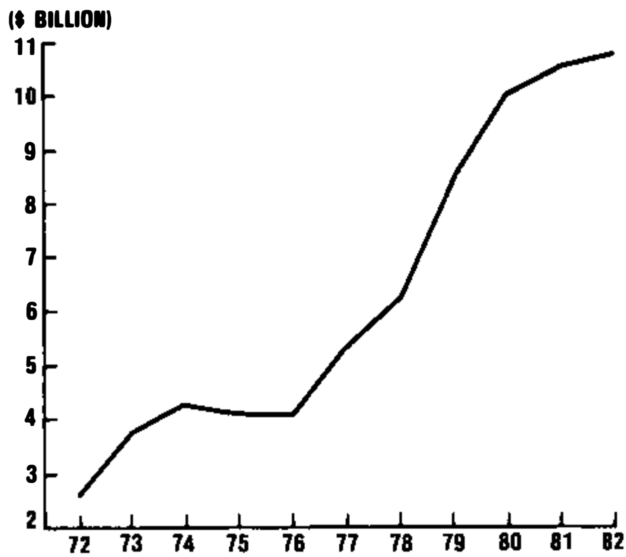

FIGURE 16. Computer industry capital spending, 1972–1982. (Source: Standard & Poor's Corporate Compustat.)

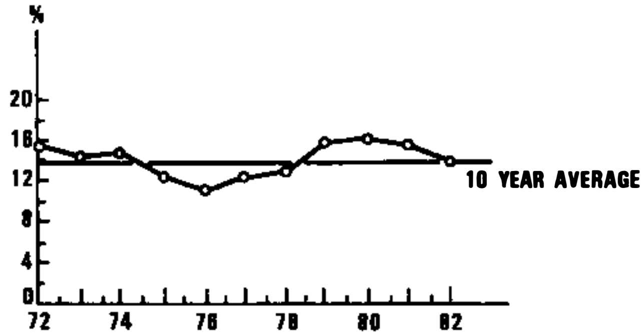

FIGURE 17. Computer industry capital expenditures as a percentage of net sales. (Source: Standard & Poor's Corporate Compustat.)

tronics industries to put their technology products into broad use. In the United States, electronic computing equipment firms (Standard Industrial Code 3680) have increased capital spending by a factor of 3 over the past 10 years (Figure 16). However, if these figures are normalized as a percentage of sales, they show a relatively flat trend that has declined over the past 2 years (Figure 17).

To determine whether or not this level of capital investment is adequate to maintain our share of the world market is extremely difficult. A relative comparison of capital investment indicators, however, can provide something of an insight into these problems. In the United States, electronics firms must achieve profit margins at a level near the average for all U.S. industry. This is twice the level for Japanese electronics manufacturers, even though in Japan, electronics firms outperform their industry average by a factor of 2 (Figure 18). This allows the Japanese to acquire capital by borrowing to a degree not acceptable in the United States, as demonstrated by the significant gap that exists between Japanese and U.S. debt-to-equity ratios (Figure 19). These two indicators document how disparate the capital investment cultures are between these two countries and how the allocation of capital and the resultant capacity to manufacture favor the Japanese.

Government R&D Support

The majority of R&D in U.S. computer and microelectronics industries is supported by company earnings. Other countries in the West-

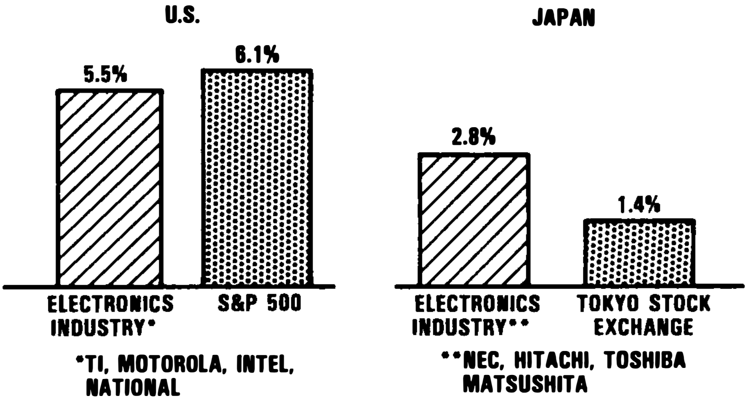

FIGURE 18. Average profit margins for U.S. and Japanese firms, 1978–1981. (Source: Annual reports, Yamaichi Research, Standard & Poor's.)

ern world—e.g., Japan, France, Great Britain, and West Germany—have established significant governmental programs to stimulate technical advancement in these industries. The essence of these programs is to use a sizable allocation of government R&D support to

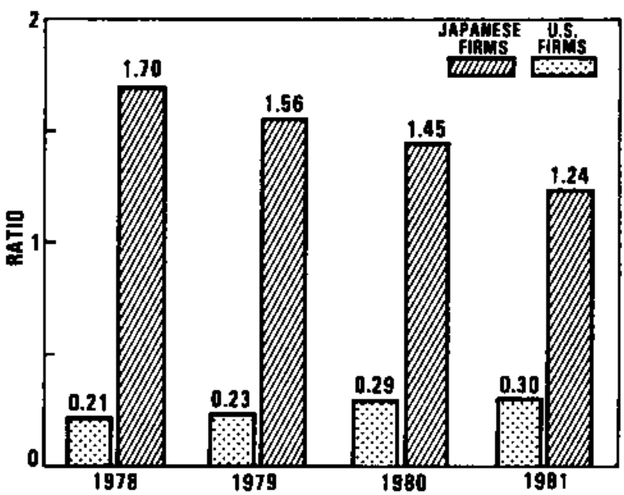

FIGURE 19. Average debt-to-equity ratios (U.S. and Japanese electronics firms). (Source: Annual reports.)

provide a national R&D focus on computers and microelectronics. The private sector is both a performer and a financial supporter of the R&D that results, usually in some relationship with government laboratories and agencies. (The centerpiece of government-sponsored programs on the world stage in the early 1980s is the Japanese fifth-generation computer program, mentioned above.) The converse of government promotion of technical development is protection of domestic industries against foreign imports, an approach that can easily become a considerable source of international friction.

Antitrust

In the United States, antitrust policy is directed toward keeping markets competitive by promoting and encouraging innovation in individual companies. The Department of Justice will review the relevant facts concerning a proposed joint research activity and state its enforcement intentions with respect to that activity. In 1980, antitrust guidelines concerning joint research ventures were issued, and such activities have recently received a generally favorable review (Department of Justice, 1980). However, enough significant, unresolved questions still exist to make the formation of cooperative research programs in the U.S. computer and microelectronics world the exception rather than the rule.

Defense Department R&D

In 1976 the Defense Science Board reported that although "computers and Large-Scale Integrated (LSI) circuits have numerous uses in the DOD, they are being developed by a broad-based industry for commercial applications. This industrial base is so strong that it appears the reduction of DOD contributions to it would have a minimal impact. The panel believes the DOD can get a better return on its R&D investment in other areas and that the DOD investment should be restricted to a limited number of very unique applications" (*Report of the Defense Science Board*, 1976).

One such application is the current Very-High-Speed Integrated Circuit Program, which focuses on the particular needs of the military for optical and signal processors. In great measure, the rest of our defense needs for microelectronics are being met by the purchase of commercial parts that have been "militarized" by subjecting them to strenuous testing and screening processes.

Computers, Privacy, and Data Security

Computer privacy is a good example of an issue that never materialized to the extent originally expected. In the early phases of computer development, personal privacy and large data bases were generally perceived as incompatible. So far, not many of the concerns have been borne out, and the debate in the United States has recently turned toward unauthorized access by citizens to proprietary data bases and computer systems and away from the traditional Big Brother perspective.

Public anxiety over the danger of "computer theft" (illegal access and manipulation of a computer's data base) has been intensified in the recent past by news stories and motion pictures that portray incidents ranging from the alteration of a student's report card to embezzlement, and even to the accidental triggering of a nuclear holocaust.

Although computer abuse has been overdramatized and is still quite small in absolute terms—about 100 cases of computer fraud are reported each year (Buss and Salerno, 1984)—the advent of local area networks presents an entirely new array of security problems that cannot be ignored. Some of the precautionary measures that can be and are being taken include privileged access (only specific subjects can access certain objects), secure callback (access to the computer is denied if a caller is not dialing from a previously authorized number), and audit trails that track violators, their violations, and their attempted violations. Although there may never be such a thing as a totally secure system, protection against most kinds of computer abuse is possible.

Transborder Data Flow

The issue of transborder data flow other than for national security reasons has received more attention in Europe than in the United States. It has several manifestations, including trade in intangibles (software evaluation), protection of personnel data (Sweden and France), and general measures to restrict the outflow of proprietary, multinational corporate data. In large part, these issues may really be a surrogate for protectionism. Tariffs based on the value of the programmed software rather than the software medium and proposed restrictions on data outflows by multinationals encourage the decentralization of computer hardware and software used by multinational corporations. If the additional hardware and software requirements are sourced in the host country, the result is a stimulus to foreign computer industries.

National Programs

Ever since the French adopted a television standard to exclude the direct import of U.S.-manufactured television sets, there has been an increase in the use of technology-based policies as political instruments. Passage of nationalistic laws regarding privacy and protection in international information flows can be seen as trade barriers. These laws are often motivated by attempts to force the performance of value-added activity to a country site where it would not have occurred otherwise. The recent increase in national laws regarding the ownership of manufacturing firms and of technology serves similar purposes. The continuing debate in the customs arena over the valuation of software and over the nomenclature of semiconductor parts is yet another example of the politicization of matter that might at first seem primarily technical.

CONCLUSION

Although the electronic computer has been a reality for less than 40 years, rapid and continuous developments in microelectronic and computer technologies have enabled the use of computers to spread throughout society. This stream of development shows no sign of abating as new technologies and applications emerge.

The United States is the overall leader in microelectronic and computer technologies, a position with significant potential for both maintenance and creation of jobs for the U.S. labor force. However, this position is not guaranteed. Foreign competition (particularly from Japan) is fierce, growing, and, in many cases, well-funded. It would seem very important that the United States understand the role of microelectronics and computers in economic growth and what policies, if any, should be implemented to enable American industries to compete successfully in the world market.

The wisdom to reap the full benefits of the technology that is now available (and which will continue to be developed) is a commodity that no country can claim with certainty. Social, economic, military, and long-term competitive considerations are complex and diverse.

Although the computer revolution is providing the tools to reshape our world, people and their institutions will determine its ultimate form.

ACKNOWLEDGMENTS

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Aerospace

Hans Mark

HISTORICAL BACKGROUND

Pre-World War II

AEROSPACE is a peculiarly American enterprise. The basic ideas that made flight possible came from elsewhere, but they were put into practice for the first time by Americans. In the early years of the nineteenth century, an Englishman, Sir George Cayley, made the intellectual breakthrough that made flight possible by recognizing that the lift forces provided by the wings of an aircraft and the thrust provided by the power plant should be treated separately. Equally important, in the case of reaction propulsion—or rocket motors—others (notably, the Chinese) had developed useful rockets several centuries ago. An eighteenth-century British military engineer, Colonel William Congreve, first developed useful military rockets. It is not clear whether they were ever decisive in war, but Congreve did provide Francis Scott Key with the image for a line in a poem that later became our national anthem. "The rocket's red glare" is familiar to all of us; the phrase refers to real rockets used by the British in the attack on Fort McHenry in Baltimore Harbor in September 1814 during the War of 1812.

In spite of the pioneering done by others, Americans can rightly claim the two most important technical firsts: the achievement of powered flight on December 17, 1903, by the Wright brothers and the flight of the first liquid-fueled rocket by Robert Goddard on March 16, 1926. These two milestones formed the basis of American preeminence in aerospace technology and have continued to inspire succeeding generations.

It is equally important to understand that American leadership in aerospace depended on an institution that was established in 1917, the National Advisory Committee for Aeronautics (NACA). Responding to the weakness of American military aviation during World War I, Congress created the committee as part of the Naval Appropriations Bill of 1917. The committee was empowered to conduct research in all of the scientific and technical areas important in aviation and was given the necessary resources to accomplish that objective. It is no exaggeration to say that the work done by NACA and its successors has been crucial to the maintenance of American leadership in aerospace. The institution, which made it possible for the United States to make consistent, long-term investments in research and in advanced technology development, has made all the difference over the years. It is largely for this reason that the field of aerospace remains an American province.

World War II

Between the world wars, Americans continued to set the majority of technical records in the field of flight: Lindbergh, Doolittle, Hughes, Post, Earhart, and other names immediately come to mind. There is no doubt that these people represented the technical superiority that was enjoyed by the United States during that period. In the field of rocketry, Robert Goddard built and flew the first liquid-fueled rocket before the Germans started their MIRAK series of rocket flights at the Raketenflugplatz near Berlin. Although the Germans, under the leadership of Walter Dornberger and Wernher von Braun, started out behind the work of Goddard in technical concept, they quickly recovered the lead because they were better organized and had much clearer objectives. The basic ideas on which the liquid-fueled rockets of Goddard and von Braun were based are still used in the development of propulsion systems for the space shuttle and for various military rockets. It is only this early work that has made possible what we are doing today (Cleator, 1936).

In aeronautics, also, the work in the United States tended to be random and not as well organized as it was elsewhere, even though we enjoyed a technical lead. The Germans, through the influence of Hermann Goering, took the lead in organizing military aviation. The Luftwaffe was a feared weapon before a shot was fired in World War II. This was due particularly to a "disinformation" campaign, carried out by the Germans, that had a particularly great influence on Charles Lindbergh, who in turn tried to influence the foreign policy of the United States toward the Germans. The Luftwaffe was indeed a formidable weapon, but it turned out to be not formidable enough. The example of the Battle of Britain is the crucial case in point. The Germans always looked upon air power as support for land power, and not really as an independent military arm. Although the Germans had some very good airplanes, it is important to remember that they never built anything like such large, long-range bombers as the Boeing B-17s, the Consolidated B-24s, and the Boeing B-29s that the United States eventually fielded. The Germans lost the Battle of Britain simply because they did not have the strategic bombers to prevail. Their basic aircraft, the Heinkel HE-111s and the Junkers JU-88s, were good airplanes, but they were range limited; therefore, the British could indeed operate many of their interceptor squadrons from air bases that the Germans could not reach.

At the beginning of World War II, in 1939, the U.S. air services were relatively weak. Although a number of advanced aircraft were in development, they did not exist in quantity and were not ready for combat. However, because of the technological base provided by NACA, the United States quickly caught up. President Roosevelt said in 1940 that we would build 50,000 aircraft, and I well remember that no one believed him. As it turned out, almost 250,000 airplanes were built in the United States during World War II, and this alone ranks as one of the foremost achievements in aeronautical technology.

There is one important area in which the Germans stayed ahead during the entire course of World War II: the field of military rocketry. If the technical tour de force of the allies during World War II was the creation of nuclear weapons, the equivalent achievement on the German side was the creation of the first long-range rocket that had military applications, the V-2. Although air power was very important during World War II, all of the evidence indicates that it was not completely decisive. Both the V-2s and the nuclear weapons appeared too late in the war to have any real impact on the outcome. The use of nuclear weapons shortened the war against Japan, but it did not change the outcome of the war in a decisive fashion.

Air power—or, more accurately, aerospace power—came to dominate the postwar world primarily because nuclear weapons and long-range rockets were combined into what John von Neumann called intercontinental artillery. There is no doubt that today the use of these weapons would indeed be the decisive factor in any conflict. It is no exaggeration to say that the strategic balance (or, as some people call it, the balance of terror) that has existed for almost 40 years has provided the framework within which the international politics of the postwar world have been conducted. It is, of course, the changes in this technological situation today that threaten to disturb the current balance, with which many people have become comfortable. I will return to this point later on, because it is perhaps the most important new development that we must take into account in structuring the foreign policy of the United States. However, before returning to this most important matter, some more history is necessary (Emme, 1959).

Commercial Aviation (1925–1965)

The first commercial air services, established in the mid-1920s, were based primarily on military aircraft that were developed during World War I. They were subsidized by the U.S. government in the form of subsidies to the operators to carry mail. (Similarly, the U.S. government later subsidized Comsat to get the country into the communications satellite business.) The early airmail services grew into the great airlines of today. There was a time when TWA stood not for Trans World Airlines but rather for Transcontinental and Western Airlines.

From a technical viewpoint, the most important area of subsidization by the government was propulsion. The great air-cooled radial engines that later powered most U.S. aircraft in World War II were developed for military purposes in the 1930s. As it turned out, such engines had the best horsepower-to-weight ratios, and their development was primarily due to a few farsighted people in the Army Air Corps, such as General H. H. Arnold, who foresaw the importance of strategic aviation. These engines were, of course, adapted for civilian use as well. The other important technical development was the creation of an all-metal airplane. Only with all-metal construction was it possible to develop airplanes that were both large enough and safe enough to be practical from a commercial viewpoint. All-metal construction and efficient air-cooled engines were combined to create the famous Douglas DC-3 in 1935. The Douglas DC-3 was really the first successful commercial airliner in the world, and over 20,000 were built. It was the workhorse of the U.S. Army's and the U.S. Navy's transport fleet in World War II, during which it was known as the C-47 in the army and the R4-D in the navy. Several thousand of these aircraft are still in service all over the world, nearly 50 years after the last one was built.

The Douglas DC-3, fine as it was, still had a limited range because it was too small. Intercontinental travel by air before World War II depended primarily on the great seaplanes operated by such organizations as Pan American Airlines. The technology for building large, land-based aircraft was not yet ready; thus, the first intercontinental airplanes were seaplanes.

Commercial aviation came into its own after 1945, when a generation of airplanes based on the great four-engine, land-based bombers of World War II was created. These were the Douglas DC-6, the Douglas DC-7, the Lockheed Constellation, and the Boeing Strato-Cruiser. Because of the operational experience gained in World War II, it was possible to calculate the operational economies of these airplanes precisely. Thus, these aircraft came to dominate commercial air travel, and they did so until the early 1960s, when large multiengine jet aircraft replaced them. The creation of the large, four-engine intercontinental transports resulted in the first great expansion of air travel in the decade after World War II. These airplanes were used by the United States but were also sold to other nations, and this was important not only economically but also politically. The pattern established shortly after the war in the creation of the large four-engine, propeller-driven transports was repeated when jet-propelled transports were introduced in the early 1960s.

The Jet Age

Just as the great radial reciprocating engines led to the development of air power in World War II, another innovation in propulsion created a new revolution in aviation—the jet turbine engine. Turbine engines were a European development initiated by an Englishman, Sir Frank Whittle, who was granted a patent on the jet turbine engine in 1930. It was a technical development deemed necessary if aircraft were ever to fly at speeds exceeding that of sound. Whittle and his collaborators in England were the first to work out the principle and then to build and test a working jet turbine engine in 1937. Work started on jet propulsion in Germany as well, with the first patent granted in 1935 to Hans von Ohain. The German work proceeded more rapidly, and the first flight of a jet-powered aircraft, the Heinkel

HE-178, was conducted in August 1939, almost 2 years before a Gloster E28/39, powered by one of Whittle's engines, flew on May 15, 1941. The first operational jet airplane was the Messerschmitt ME-262 interceptor, which was fielded by the Germans in the waning days of World War II.

At the end of World War II, the United States decided to build large, multiengine jet bombers designed to carry the atomic weapons that would eventually lead to what we today call the nuclear strategic balance. These aircraft were intended to be the Strategic Air Force, which is still in existence today as the U.S. Air Force Strategic Air Command. There were formidable technical challenges that had to be overcome to build the large jet bombers. The first was to get jet engines to operate reliably, and this meant that problems in high-temperature materials and internal aerodynamics had to be solved. It was also necessary to create the large, flexible, all-metal structures that would be designed to operate in an environment where the airplane could fly just below the speed of sound. These challenges were met, and the Boeing B-47, the first intercontinental all-jet bomber, was put into operation in 1951, 6 years after the end of the war. The much larger Boeing B-52 became operational in 1955 and is still in service. These airplanes formed the backbone of our nuclear strategic force and maintained the strategic deterrent well into the 1960s.

At the same time, supersonic flight was achieved by small experimental aircraft designed for that purpose. The "sound barrier" was broken for the first time (on October 14, 1947) in level flight by U.S. Air Force Brigadier General Charles Yeager, flying the rocket-powered Bell X-1, the first of the famous X-series experimental aircraft. These airplanes were built during the late 1940s and the 1950s and were developed under a joint program by the NACA and the U.S. Air Force—another example of the pervasive technical influence of the NACA.

The last of the X-series airplanes was the famous X-15, which was a true rocket airplane. The North American Aviation X-15 was the first manned vehicle to go into space, reaching an altitude of over 67 miles (354,200 feet) during a flight by the National Aeronautics and Space Administration (NASA) chief test pilot, Joseph A. Walker, on August 22, 1963. The X-15 had most of the features of the space shuttle and was in a real sense the prototype aircraft for the shuttle. It is no accident that Neil Armstrong, the first human to set foot on the moon, was an X-15 pilot. I should point out that the first rocket aircraft (the

Messerschmitt ME-163) was actually developed by the Germans, in 1944. It was an important technical step, but it was clearly not developed further at the time because the Germans were so close to defeat in World War II.

The commercial impact of jet aviation was, if anything, more important than the military impact. Once operational experience was gained with the Boeing B-47s, the Boeing B-52s, and the tankers (the Boeing KC-135s, which made these bombers truly intercontinental), commercial operations were also started. Starting with the Boeing 707, a direct modification of the Boeing KC-135, commercial operations burgeoned. In 1959, the last year before large jet aircraft came into service, U.S. air carriers flew 36.3 billion passenger miles. In 1982 they flew 259.03 billion passenger miles, which is an enormous expansion by any measure. The technology of the large passenger jet has made world travel commonplace. A single Boeing 747 carries more people back and forth across the Atlantic in a season than the *Queen Mary* did in her heyday, and the airplane can do so at one-tenth of the cost.

World travel is now commonplace, and there is no doubt that the movement of millions of people around the world has had profound political effects. In many regions of the world, national boundaries have essentially disappeared because of air travel. This is particularly true today in Western Europe, where national boundaries still exist, but where the people themselves behave as if they did not. For example, Moslems all over the world make their traditional pilgrimages to Mecca by jet transport. Many millions have made trips never before possible, and this has clearly expanded human horizons and the human imagination. Today's young people may be the first truly international generation. All of this has had incalculable political effects that are now only dimly perceived. It is not even clear whether the easy travel we enjoy today will in the end be beneficial or whether it will simply exacerbate the differences between people that have always existed. What is certain is that all of this is due to the technology that flowed from the jet turbine engine and the all-metal airplane; furthermore, most of this is due to American technology. Go to any international airport outside the Communist area, and you will find aircraft bearing the flags of all nations. The vast majority of these aircraft were built in Seattle, Los Angeles, or some other place in the United States, and the engines, as well, came from Lynn, Massachusetts, or Hartford, Connecticut. This exercise of American influence may be subliminal, but it is pervasive, and we should not forget it. More tangibly, aeronautical products account for something like $20 billion worth of exports per year, second only to agricultural products. This also is a result of the United States' dominant position in aeronautical technology.

It would be a mistake here not to mention the important influence of American military aircraft as well. We have already talked about the strategic bombers, but there are other military aircraft that should be considered. Two examples illustrate this point. In 1978, a bitter civil war was raging in Zimbabwe (then called Rhodesia). An agreement was reached to hold elections, and the British provided a peacekeeping force to oversee the elections. This force was brought in and supplied by U.S. Air Force Lockheed C-141 transports. It is doubtful whether a more or less satisfactory political solution in Rhodesia-Zimbabwe could have been found without the aid of these very capable aircraft.

The other example is an incident that occurred in 1982. When Israel invaded Lebanon to destroy the Palestine Liberation Organization's military strongholds in the southern part of that unhappy nation, it fought an air battle against the Syrian Air Force. In a matter of hours, over 70 modern, Russian-built Syrian aircraft were destroyed by American-built, Israeli-flown McDonnell Douglas F-15s and General Dynamics F-16s. The Israelis did not lose a single aircraft, demonstrating beyond all doubt the superiority of modern American military airplanes.

The jet age can truly be called an American creation, and the full impact of what this new technology will bring is still to be assessed. It is not too early, however, to draw at least some conclusions. One is that we have made world travel commonplace, providing millions of people with experiences that were simply not available for prior generations. Will this make it easier to conduct a foreign policy aimed at maintaining a stable world? It is possible at least to hope that this is true, but we will only know this once the generation that has benefited from this circumstance assumes full political leadership. Another conclusion is that the jet airplane has made it possible to project military power anywhere in the world. In many instances this has contributed to stability—the Berlin Airlift, the situation in Rhodesia-Zimbabwe, and the stabilization of the Congo and a number of other places. We must continue to use this far-reaching capability to maintain stability and world peace. There is no doubt that the opportunity is there (Howard and Gunston, 1972).

The Enterprise in Space

The years after World War II were crucial in the development of seminal ideas. The great mathematician and public servant John von Neumann saw in 1945 that the existence of nuclear weapons and the emerging technology of large, liquid-fueled rockets would lead to the creation of what he called intercontinental artillery. Von Neumann saw that the great intercontinental bombers were, to some extent, a stopgap and that eventually the intercontinental ballistic missile (ICBM) would be the centerpiece of the nation's nuclear strategic forces. The development of these rockets—based on the principles already proven by the Germans with their V-2s—happened in a remarkably short time. A decade after the end of World War II, the first ICBMs were put into the field. The Russians were not far behind, and because their nuclear warhead technology was more primitive than ours their less efficient nuclear weapons were heavier, they actually built larger rockets than we did during that period. It was not a great step from the ICBM to space. A rocket capable of throwing an 8,000-pound warhead halfway around the world could also put an artificial satellite into earth orbit. Thus, the "enterprise in space" started with the development of the ICBM.

In 1946, the RAND Corporation published a really remarkable paper (Clauser et al., 1946) in which almost all of the things that have been done in space for the past 40 years were foreseen. These things ranged from the creation of communication satellites to the exploration of the moon and the planets in our solar system. The paper started with the premise that the ICBMs could easily be modified to become space boosters. Everything followed from this basic idea. The authors of the RAND paper also foresaw the political and symbolic importance of making the first steps into space. It is unfortunate that the American political leadership in those years did not perceive this point.

On October 4, 1957, the Russians startled the world—and shocked the American people—by launching the world's first artificial satellite, *Sputnik I*. Not only that, but 2 months later they launched a large scientific research satellite that weighed well over a ton. With these events the race into space was on. The political leadership of the United States had taken the position that earth satellites were purely scientific instruments, and therefore the American program to orbit an earth satellite (Project Vanguard) was carried out at a leisurely pace, driven by the scientific requirements of an international scientific program, the International Geophysical Year. Once the Russians orbited *Sputnik*, resources on the American side were quickly mobilized, and on January 31, 1958, less than 4 months after the Russian launch, the first successful American-built satellite (*Explorer I*) was placed into earth orbit. That the United States was able to respond so quickly was due primarily to the foresight of Wernher von Braun and his collaborators—the wartime developers of the V-2 rocket. They were brought to this country after the war to continue their research and development work on large military rockets. Before 1957, von Braun's group was prohibited from working on earth satellites and their launch vehicles. With great technical virtuosity and at considerable bureaucratic risk, they put together the rocket and, with the help of the Jet Propulsion Laboratory, the payloads for *Explorer I*—even before the Russians launched *Sputnik I*—anticipating that their hardware would eventually be needed and used.

What was much more important than the technical success of *Explorer I* was that in 1958, stung by the Russian space achievements, the United States in short order created the institutions that would rapidly permit it to recapture and then keep the lead in the human race's enterprise in space. These institutional arrangements were founded on NACA, which so successfully provided the basic technology to maintain American leadership in aviation. In the fall of 1958, a new organization—the National Aeronautics and Space Administration (NASA)—was created. The new organization was given a very broad charter to maintain American leadership in space and aeronautics. Recognizing the political and symbolic importance of space operations, NASA was created specifically as a civilian organization that would conduct its activities in a completely open manner under the full glare of publicity. Furthermore, the law under which NASA operated specified that those space operations important to the national security would be conducted by the Department of Defense.

The success and the impact of American space operations have been largely the result of this important and unique political arrangement. Another important feature of NASA is that the traditional technical excellence of NACA was maintained in NASA. The old NACA formed the bedrock upon which the new NASA was built. In addition to NACA, several elements operated up to that time by the U.S. Army (the Ballistic Missile Organization at the Redstone Arsenal in Alabama and the Jet Propulsion Laboratory in California) and the U.S. Navy (the Naval Research Laboratory, a portion of which was later split off to become the Goddard Space Flight Center) with space-related activities were transferred to the new agency. Once these arrangements were completed, the United States was ready to recapture the leadership in space operations.

The Race to the Moon

Five months after assuming office as President in 1961, John F. Kennedy set a goal for the nation: to put a man on the moon and bring him back safely before the year 1970 (speech by President Kennedy, May 25, 1961). There is no doubt that the President's decision was motivated by important political and foreign policy considerations. The Russian feat of orbiting the first man, Yuri Gagarin, in April 1961 was clearly a major stimulus for the President's move. By that time it was clear that visible technical achievements in space technology were widely accepted as a measure of "national competence," and in that sense it was important for the United States to recapture the lead from Russia.

President Kennedy also recognized that, in addition to the influence on foreign policy, there were domestic advantages. The trip to the moon became something around which certain major elements of American technology could be focused. An interesting case in point is the electronic control system that was developed for the lunar excursion module. This was the first time a completely "fly by wire" system was used. Such a system has now been incorporated into advanced military aircraft, such as the F-16, and will undoubtedly be applied to the next generation of civil aircraft as well.

The race to the moon was on, and there should be no doubt that it was a race. The Russians deny it now, but they made a major effort to get to the moon before the Project Apollo astronauts. The Russians cancelled their effort to put a man on the moon after they sustained several costly space failures late in the 1960s. The landing of *Apollo 11* on the moon in 1969 clearly reestablished American leadership in space operations, a lead we have not relinquished. There is no doubt that the success of Project Apollo had a profound impact on the rest of the world and gave strong encouragement to our friends around the world during a period in American history when it seemed that we had lost our way and our collective will. It was the one shining event in a decade that started with great promise but was ultimately characterized mostly by failure. I remember visiting Yugoslavia during one of the Apollo missions, and I was amazed by the cheers we received everywhere when people discovered that we were Americans. There was no doubt that the vast majority of the people we met were pleased that we had bested the Russians.

Subsequent to the Apollo program, two important goals were achieved—one technical and the other political—using hardware that was developed for Apollo. The world's first orbiting space laboratory, Skylab, was launched in 1973 and was subsequently visited three times by astronaut crews. Many new things were learned about the behavior of people in space and about some things that can be done in space related to processing and manufacturing. These will be of increasing importance as the shuttle program matures and as we start to plan for a permanent space station.

The other project was Apollo-Soyuz. Both President Nixon and Secretary of State Kissinger understood the popular appeal of achievements in space operations. Accordingly, they looked for a space project to underscore the policy of detente with Russia that they were pursuing at the time. When approached with this problem, NASA proposed a linkup in space during which an American Apollo module and support unit would dock with a Russian Soyuz spacecraft. Three American astronauts would meet two Russian cosmonauts in space and shake hands, thus symbolizing the Nixon-Kissinger policy. The Apollo-Soyuz project was successfully executed in 1975. It is not clear what effect Apollo-Soyuz actually had, because the political imperatives that existed in 1971, when the project was conceived, no longer really applied in 1975. What is important is that at the highest national level, the potential symbolic foreign policy importance of space operations was clearly recognized (Levine, 1982).

SPACE OPERATIONS AND THE ADVANCEMENT OF SCIENCE

The authors of the 1946 RAND report (Clauser, et al., 1946) foresaw that space operations would lead to many new scientific discoveries of great significance. Their expectations have been fully justified. Starting with the lunar orbiters and the Surveyors in the early 1960s, we have made close flybys of landings on all of the planets in the solar system except Uranus, Neptune, and Pluto. We have sent two spacecraft (*Pioneer 10* and *Voyager II*) on journeys out of the solar system. Perhaps the things we have done in space-based astronomy will be even more important and spectacular than what has been done in planetary exploration. Space-based telescopes have probed the outer reaches of the universe and brought us significantly closer to understanding some of the most fundamental phenomena in cosmology and how these might be related to the ultimate structure of matter.

There is no doubt that the United States enjoys a commanding lead over its principal competitors, the Russians, in space science. From a cultural viewpoint this is very important, because we can only really be a great nation if we value science. Our scientific work in space has important international implications, which is our major concern here. Almost all space science programs executed by the United States have had participants from other nations. Because of the open nature of the American space program, these international collaborative efforts can be easily arranged, and they have been very fruitful. An international network of scientists exists that has come to rely on the United States to provide opportunities to perform research in space. Although this group is not necessarily important in day-to-day questions involving foreign affairs, many of its members are influential in the international scientific community. As such, they play a role in helping provide the intellectual atmosphere in which foreign policy is conducted.

As important as this scientific work has been, especially in providing new horizons for the human imagination, scientific research based on looking at the earth from space may be even more important. For the first time we really understand global weather patterns, and we have actually been able to construct mathematical models of the earth's atmosphere that have great value in making long-range weather forecasts. Observation satellites, such as Landsat, have yielded absolutely remarkable results. We have been able to look at trends—such as deforestation, for example—on a comprehensive global basis, and we have been able to assess the long-term consequences of these trends. We have made worldwide crop assessments routine, using Landsat data, and we have provided accurate maps of large regions of the world, such as the Amazon Basin, for which none existed before. The ground data receiving stations for the Landsat system are located all over the world, and many nations participate with the United States in the Landsat program. Twelve countries now receive data directly from Landsat through their own ground stations (China is establishing one), and many others participate with the United States in research programs that are of particular interest to them. The United Nations Environmental Program (UNEP) uses the data from the Landsat system as a primary source of information for the evaluations it makes. In addition to Landsat, the United States has flown and now operates a series of more specialized scientific satellites designed to observe certain features of the earth's surface in much greater detail. Examples of these are Seasat, which was designed to observe the ocean, and GEOS, which permits very precise determinations of the shape of the geoid. GEOS is particularly important because it allows us to make very accurate measurements of the motion of one part of the earth's surface with respect to another, thus contributing to the verification of the theory of plate tectonics and continental drift. There is reason to hope that work done with this satellite will permit us to make progress toward the prediction of earthquakes.

It is obvious that all of these things have important international implications. Although the United States has been a leader in developing the necessary international arrangements to use the information obtained from earth observation satellites, there has been considerable ambiguity within successive American administrations regarding the proper government role in the development of earth observation satellites. Some have advocated that the earth observation satellites developed by NASA and operated by the National Oceanic and Atmospheric Administration (NOAA) be turned over to the private sector for operation at a profit, since the government has no business in the operation of these satellites beyond the research phase. There are formidable financial and institutional barriers to achieving this objective, and it might be worthwhile to explore the possibility of using the impact on our foreign relations to keep these programs going until we sort out our internal problems. The failure to develop a proper rationale for the operation of earth observation satellites by the United States will inevitably lead to a situation in which other spacefaring nations, such as Russia, France, and possibly Japan, will take over the business. The United States cannot permit this to happen. The very positive effect that the sharing of earth observation data with other nations has had should be reason enough to keep these activities going. It is to be hoped that a broader look at the whole question of earth observations, including those performed for the purpose of national security, will lead to a better understanding of the vital role that the United States can and should play in this very important area (Holdgate, et al., 1982).

SPACE OPERATIONS AND THE NATIONAL SECURITY

The Russians remain the principal adversaries of the United States in the world. Russia has a closed society that operates under very strict rules regarding what foreigners can and cannot learn. All of the information media are under strict government control, and all mail leaving the country is strictly censored. Travel for foreigners within Russia is heavily restricted, and visitors are closely watched. The Russians have a dangerous paranoia about national sovereignty, and unfortunately, they act accordingly. Nevertheless, world security and stability require that we have at least some minimal information about what the Russians are doing, and we have applied aerospace technology for this purpose for many years.

In the early 1950s it was extremely important to learn what the Russians were doing in nuclear weapons technology. Accordingly, an aircraft was designed and built that could operate at extremely high altitudes that were then beyond the range of surface-to-air missiles and above the maximum ceiling of interceptor aircraft. The result of this effort was the famous Lockheed U-2 reconnaissance aircraft, which was developed by Kelly Johnson in a major technical tour de force. Overflying Russia with a U-2 aircraft was a violation of Russian sovereignty, and it was expected that the Russians would make every effort to shoot down a U-2. Eventually (in 1960), they accomplished this objective and although U-2s and their companion reconnaissance aircraft, the Lockheed SR-71s, are still in active service today, they are operated in such a way that there are no violations of Russian airspace.

The shooting down of Gary Powers's U-2 coincided roughly with the rapid growth of space operations. It was natural at the time to see whether some of the functions performed by the U-2s and the SR-71s could also be performed by earth-orbiting satellites. In that way, the overflight problem could be avoided at least until the capability to shoot down satellites existed. Accordingly, a series of highly classified observation satellites were developed for this purpose, and these satellites have assumed an ever more important role over the years. Perhaps the most important function carried out by these observation satellites is the monitoring and verification of arms control agreements. There is not much doubt that such agreements would not be possible unless they could be verified. In the 1972 strategic arms control agreement that we negotiated with the Russians (SALT I), there is a provision that neither side will interfere with the other's "national technical means of verification." In 1978 President Carter revealed for the first time that these national technical means were photoreconnaissance satellites operated for the purpose of arms control verification. The satellites we developed for this purpose greatly reduce the uncertainty that our political leaders face in making decisions, and in that sense, the existence of these satellite systems contributes to world stability and peace (Wolfe, 1979).

In addition to the surveillance satellites, the military establishment also operates weather observation satellites, communications satellites, and satellites designed to provide warning of a major strategic missile attack. These are all extremely important functions, and it is important to recognize that none would have been possible without the vigorous development of aerospace technology by the United States.

There is not much doubt that the Russians are aware of the importance of our space operations to national security. Since 1972, the Russians have been testing a system designed to shoot down our satellites, using their so-called ASAT, or antisatellite system. Although their system is relatively primitive from a technical viewpoint, it is capable of destroying satellites in relatively low earth orbits. It is also important to recognize the Russian lead in this technology; at present, the United States does not have antisatellite capability. Why did the Russians develop an antisatellite system, and why haven't we? We do not know precisely, of course, but we can speculate. On the one hand, they know that our satellites are very important to us because of the closed nature of their society. On the other hand, their surveillance satellites are not nearly so important to them because they have other ways of gaining information about what we, in an open society, are doing. We therefore felt it less worthwhile to produce an antisatellite system, and the asymmetry that exists today in this capability resulted.

All of this led to renewed concerns about the deployment of weapons in space. Russia and the United States have several agreements that limit the deployment of weapons in space. We have agreed not to deploy weapons of mass destruction in space and to limit certain space operations in other areas (Howard and Gunston, 1972). Early in his administration, President Carter became concerned about Russian antisatellite tests and proposed to President Brezhnev that Russia and the United States initiate negotiations on a treaty to eliminate antisatellite weapons. Negotiations were carried out for about 2 years, but they were not successful. The United States' lack of antisatellite capability gave the Russians no incentive to negotiate seriously, and they did not do so. The negotiations were terminated when it became obvious that no progress would be made. One result of the unsuccessful talks is that the United States is now well on the way toward developing an antisatellite capability that will provide important leverage if negotiations to control antisatellite weapons are resumed.

On March 23, 1983, President Reagan made a very remarkable speech. He said that progress in technology was such that the time had come to think seriously about developing a defense against ballistic missiles. There is no doubt that such a development would be a far-reaching step that would eventually lead to profound changes in the strategic balance. For almost 40 years, what we call strategic stability has been maintained by strategic nuclear forces operated under the doctrine of "mutually assured destruction." The essential idea is that each of the two superpowers possesses nuclear forces deployed in such a way that each force can survive a surprise attack from the other. If this condition can be preserved, then the doctrine of mutually assured destruction works. Each side is deterred from attacking the other, because even if the attack succeeds, the destruction of the attacker is assured. In the long run, it will probably not be technically feasible to deploy nuclear forces in such a way that a nation can survive a surprise attack and this, I believe, is the essential point that must be recognized. Therefore, new steps must be taken to maintain strategic stability, and the application of new techniques is necessary to accomplish that end. These new technologies include upgraded "smart" missiles that can detect and then destroy incoming ballistic warheads, new directed-energy weapons that can be based in space to hit attacking ICBMs almost anywhere in their trajectories, and new surveillance systems that will provide the data necessary to orchestrate the defense. All of this is within the realm of technical possibility, and the President has called for the development of a technical program that will lead to the creation of such a defensive system by the end of this century.

In the near term, two kinds of defensive systems seem to be feasible, and neither of these requires very large extrapolations of current technology. One is an antiballistic missile system designed to defend fixed ICBMs in their silos. Sensor and guidance systems are now so precise that such antimissile missiles can actually hit incoming nuclear-armed warheads directly, thus requiring no explosive charge to destroy their targets. This is called kinetic energy kill, and it makes antiballistic missile systems feasible today. In 1969, when a great public debate was carried out over the question of defense against ballistic missiles, the antimissile systems of that day required nuclear warheads to kill the incoming missiles. It was judged at the time (correctly, I believe) that such a system would be impractical because of the vulnerability of some of the ground facilities, such as the radars, and the collateral damage that the defender's nuclear explosions might cause. Consequently, no serious deployments of military value were made.

An antiballistic missile system with nonnuclear, kinetic-energy-kill warheads does not have the drawbacks of the systems considered a decade and a half ago. Sensors, computers, and guidance systems can now be built into the missiles themselves, eliminating large, vulnerable facilities on the ground. Even if such a system were only 50 percent effective, it would have military value because it would in essence reduce the number of warheads available to a potential attacker for destroying the ballistic missile force of the adversary. The deployment of such a system—provided that it is "leaky"—would deter a potential attacker because the attacker could no longer be certain that he could destroy the ICBM force of the defender. Thus, such a system would make it possible to maintain the doctrine of mutually assured destruction for a while longer, until more "perfect" systems were developed and deployed.

Another interesting idea that has been considered for well over a decade is to develop laser-armed aircraft that can patrol the ocean off our shores and shoot down submarine-launched ballistic missiles in the boost phase of their trajectories. The U.S. Air Force has recently demonstrated that it is feasible to shoot down fast-moving missiles with a high-intensity laser mounted on a large jet transport. Such a laser carried by a Boeing KC-135 has destroyed five air-launched Sidewinder missiles fired in rapid succession. By a reasonable extension of this technology, it should be possible to develop lasers that can shoot down submarine-launched ballistic missiles at ranges that are great enough that the number of aircraft on patrol can be kept reasonably small. It is important to hit the submarine-launched missiles in the boost phase, because they are then easy to detect and also relatively "soft" to the laser damage mechanisms.

The deployment of a force of aircraft that could shoot down submarine-launched ballistic missiles would have important military value. The primary effect of such a deployment would be to force the Russians to move their missile-carrying submarines away from our shores and into the open ocean. Such a move would lengthen the flight times of their missiles from a few minutes to the amount of time required for land-based missiles starting from the Eurasian continent. Thus, the aircraft deployment contemplated here would reduce the danger to our coastal population centers of a surprise attack. The ability to conduct such a surprise attack—a bolt out of the blue, if you will—is considered destabilizing under the doctrine of mutually assured destruction. The capability to conduct such an attack might provoke the potential victim to launch a preemptive first strike. Keeping the Russian submarines off our shores to prevent short-notice attacks with depressed-trajectory missiles would, therefore, increase stability. Thus, the two systems that could be deployed in the near term—say, in the next 10–15 years—would actually preserve the nuclear balance of forces, based on the doctrine of mutually assured destruction (Mark, 1982).

In the longer term, however, it should be possible to build more nearly perfect defensive systems by deploying various antimissile weapons on space-based platforms. Using such methods, a layered system could be built that might prevent more than 99 percent of the warheads launched by a potential attacker from reaching their targets. Such a system would indeed change the military doctrines under which the nuclear forces of the world are deployed. A situation would be created in which deterrence based on the fear of assured destruction of an attacker could no longer be sustained. It is difficult to make any really firm statements about the time scale on which the deployment of such a system could be achieved. My own guess is that by the middle of the next century a defensive system could be in place that would make it necessary to change the doctrine of mutually assured destruction. To achieve this objective, the necessary research and development must be started now (Graham, 1983).

There are very good reasons to believe that all of these things can eventually be done, and it is therefore extremely important to start now to think through the political and foreign policy implications of the existence of such defensive systems. One particularly important point must be considered. At least some defensive systems can very likely be built without the deployment of any nuclear warheads. Therefore, nonnuclear powers, such as Japan, Germany, Israel, and others, who have the technical capability might also deploy effective antiballistic missile systems. Quite possibly, therefore, these nations, if they deploy such systems, could be much less dependent on the United States for defense than they are today.

The President's strategic defense initiative is probably the most far-reaching step he has taken during his entire administration. It marks a watershed in strategic thinking, because the President has recognized explicitly that the doctrine of mutually assured destruction may not be technically supportable in the long run, and he has challenged the American technical community to develop defensive systems that will create a new and stable strategic balance. Concern over the President's move has been expressed in many quarters, but once the issues are clearly understood, I believe people will realize that we have no choice but to go ahead with the development of defensive systems. We know that the Russians are already working on defensive systems, indicating that they have also recognized that the era of mutually assured destruction is slowly ending. The coming decade will be dangerous as we start the shift from one nuclear strategic concept to another, but there is no doubt that the shift will occur. We cannot afford to let other nations—particularly, the Russians—exceed us in the capability of fielding strategic defensive systems. Instability will surely result if we let that happen. The best and only course is the one the President has suggested, and that is to apply our great strength in aerospace technology to create the strategic defensive system that the President has in mind (Mark, 1984).

SPACE OPERATIONS AND THE ADVANCEMENT OF TECHNOLOGY—COMMERCIAL IMPLICATIONS

Two important issues must be examined when looking at technology and its commercial implications: one is the direct application of space technology to commercial enterprises, and the other is the list of technical spin-offs that has resulted from the move into space. One of the important predictions of the 1946 RAND report was that satellites would be used to establish a worldwide communications network. Less than 40 years later, this objective has been accomplished. Not only that, but the satellite-based communications industry is also very profitable, and because of its technological leadership, the United States still dominates this important field. The commercial communications satellite industry was established in 1962, when a government-sponsored corporation, Comsat, was established to see what could be done to exploit the commercial potential of communications satellites.

At about the same time, NASA launched the first experimental communications satellite into geosynchronous orbit.* These NASA

*A geosynchronous orbit is an equatorial orbit at an altitude of about 22,000 nautical miles in which the satellite maintains its position permanently above the same point on the earth's surface.

satellites, the Applications Technology Satellites, became the prototypes for the subsequently developed geosynchronous commercial communications satellites that now form the backbone of our communications satellite system. In this case, NASA supported the communications satellite industry in much the same way that it (and earlier, NACA) supported the aeronautical industry. The development of satellite communications has had very important international implications as well. In 1964 the United States led in the formulation of International Telecommunications Satellite Organization (INTELSAT). Formally established in 1973, INTELSAT now has 108 member nations that use its services. The United States is still the dominant member of INTELSAT because of continuing U.S. technical leadership; for example, the INTELSAT satellites are still manufactured by the United States and put into orbit mostly by American launch vehicles. However, this situation is changing. The French now have an operational launch vehicle, the Ariane, that is capable of placing commercial communications satellites into geosynchronous orbit. Furthermore, both the Europeans and the Japanese have growing communications satellite industries that are becoming rapidly competitive with that in the United States.

To maintain the competitive edge we now have in communications, NASA (in collaboration with the communications satellite industry) is proposing the development of a new program, the Advanced Communications Technology Satellite (ACTS) program. The latest technical advances, including operation at higher frequencies, rapid beam switching, and onboard data processing, will be incorporated on satellites that use this new technology. Hopefully, the new technologies that will be incorporated into the next generation of communications satellites will maintain the technical lead enjoyed by American satellites in this very important area (Smith, 1976).

At present, satellite-based communications systems constitute the only example of a successful commercial enterprise that depends on operations in space. Other possibilities are on the horizon, but so far they are only a gleam in the eye. Perhaps the most fascinating of these is the possibility of using the zero-gravity environment in an orbiting vehicle to manufacture items that cannot be made in the gravity field on the earth's surface. The best candidates for such manufacturing operations are those in which small quantities of very special, high-value materials are produced, thus minimizing the weight that has to be carried into orbit. The first Spacelab flight, executed in November 1983, was very encouraging in this respect. This criterion applies very well to the biological materials that are produced in the continuous flow electrophoresis apparatus that has been flown on five space shuttle missions. During the course of these flights, it has been demonstrated that there is an improvement in the ability to separate the materials of interest by something like a factor of 5,000 over what can be done on the ground. It is too early to tell whether this factor is enough to assure a profitable operation. A heartening sign, however, is that the development work on the instrument has been funded by private capital under a joint venture agreement between a pharmaceutical house (Johnson & Johnson) and an aerospace company (McDonnell Douglas).

In addition to direct commercial applications of the space operations cited in the previous paragraphs, there is the matter of *spin-off*. This term usually refers to the application of technology originally developed for the space program to other purposes. Perhaps the classic example is solid-state electronics. The development of the first transistors in 1948 coincided with the effort to create the first ICBMs. It was recognized immediately that electronic control systems based on the transistor would be much lighter in weight and would consume much less power than conventional control systems based on vacuum tube technology. Thus, the ICBM program, and later the space program, provided essentially unlimited financial support for the early development of transistor-based electronics. The consequences—economic and social—of all this are well known. The revolution in communications and information processing would have been impossible without the transistor, and transistor technology would not have developed as quickly without the spur provided by both the military and the civilian space programs.

Another very important area in which there have been significant technological spin-offs is materials. Space operations put a special premium on lightweight (in structures), high-temperature-resistant (in engines), and fire-resistant (for interiors) materials. A whole new generation of structural metals, alloys, and synthetics have been developed that have found applications in every nook and cranny of the economy.

These are only two examples; there are many more. Attempts have been made to quantify the economic impact of these spin-offs. The pessimists say that it would have been cheaper to develop all of these products for their own sakes rather than get them as spin-offs from other efforts. Those of us who know how the development process works know that this is simply not true. Genuine advances are made only when really tough technical requirements are set, and most of the products derived from spin-offs would not exist today without the spur of space operations, because normal commercial requirements are not that stringent. The optimists, on the other hand, make a different calculation. In her book *The Political Economy of the Space Program*, Mary A. Holman estimates that for every federal dollar invested in the American space program, 14 have been returned to the general economy. The truth is probably somewhere in between (Holman, 1974).

THE SPACE SHUTTLE AND THE PERMANENT PRESENCE IN SPACE

About 1 year before the successful landing on the moon on July 20, 1969, then-NASA administrator Thomas O. Paine initiated a series of studies aimed at developing what was called the Post-Apollo Program for NASA. These studies were carried out by several groups (the Space Task Group, as well as several internal NASA committees). A consensus emerged that the next step would somehow involve the construction of a permanent operating base in earth orbit—that is, a space station. It was also clear from these early considerations that if a substantial space station were built, then some kind of reusable "shuttle" vehicle would be necessary to keep the station occupied and supplied. Thus, the concept of the reusable space shuttle was born. As things turned out, the political leadership at the time decided that not enough money was available to initiate both a space station program and a shuttle program. Since the space shuttle was technically more difficult to develop than the space station, it was deemed to be the pacing item in the program, and so a decision was reached to build the space shuttle first. It was felt that the space station would come later, once the shuttle was in operation (Mark, 1977).

The space shuttle program was initiated in February 1972, when President Nixon gave final approval to the space shuttle proposal developed by NASA. At the time, NASA promised to develop a reusable space shuttle launch vehicle based on the "stage-and-a-half principle," which would deliver a 65,000-pound payload to a 28.5° inclination orbit. NASA also said that the first flight would be carried out in 1978 and that the development cost would be something on the order of $6.5 billion in 1972 dollars. As it turned out, the *Columbia*, the first shuttle orbiter, flew for the first time in April 1981. The total development cost was approximately $9.0 billion in 1972 dollars. The vehicle has the capacity today to deliver about 60,000 pounds, although further payload improvements are expected. Even though the original cost, schedule, and performance goals were not quite achieved, the space shuttle program has definitely been a success by any standard of measurement.

In addition to its technical success, the shuttle has been a political success much beyond the expectations of those of us who were involved in the development program. The shuttle has attracted much more public attention both in this country and abroad than we orginally expected. A good example of this is the trip to Europe made in May and June 1983 by the *Enterprise* and the Boeing 747 Shuttle Carrier Aircraft. Well over 2 million people went to see the *Enterprise* at the four airports (Bonn-Cologne, Paris, Rome, and London) where the shuttle was on exhibit. The news media in all of the places that the shuttle visited provided very positive coverage of the event. Without question, the impact of all of this has been extremely positive for the United States. Without question, space exploration still has a very basic appeal to people all over the world.

There are still a number of unanswered questions about the ultimate operation of the space shuttle, despite the great success of the program. Will we depend exclusively on the shuttle, or should we retain or develop unmanned launch vehicles? How should the shuttle eventually be operated? What can be done to make certain that safety of operation of the system is maintained and improved? The last question is particularly important, precisely because of the political popularity of the shuttle, along with the other reasons for maintaining safety of flight. It is of the utmost importance that the effort to preserve safety of flight remains the first priority in the space shuttle program as we approach the operational era of the shuttle.

The development of the space shuttle has resulted in the creation of a number of new hardware components on which a new generation of space launch vehicles can be based. The large solid rocket boosters can be modified so that they can replace most of the expendable launch vehicles in service today. Furthermore, launch vehicles based on the new technology would be much less costly than the expendable launch vehicles currently in use. In addition, the space shuttle main engine could also be used in combination with the solid rocket booster to develop very large launch vehicles capable of putting payloads of up to 500,000 pounds in near-earth orbit.

Now that the space shuttle development program is near completion, the next step is to initiate the development of the space station. In his State of the Union message delivered on January 25, 1984, President Reagan made a commitment to construct a permanently manned space station in near-earth orbit (Waldrop, 1984). The President called for the development and deployment of such a space station within the next decade, and, recognizing the important international impact of American efforts in space, he called on our friends and allies around the world to collaborate with us in taking this far-reaching step. The essential purpose of the space station would be to provide an operating base in space to support future activities. The space shuttle, which will change fundamentally the way business is done in space, will eventually lead to the construction of a space station.

Perhaps the most important change is that in the future, satellites in near-earth orbit will be repaired and refurbished. Instead of deactivating or deorbiting satellites after their "useful" lives are over, as we do now, satellites will become permanent facilities in orbit, because the shuttle will make it possible to resupply and refurbish satellites in orbit. The space telescope, for example, has been designed from the very start to be such a permanent facility. The plan is to revisit the telescope periodically with the shuttle and to perform various maintenance and refurbishment functions. For example, the focal plane of the telescope has been designed in such a way that the detecting instruments can be replaced with new ones if better technology becomes available. It will therefore be possible to continually upgrade the performance of the space telescope.

It is very likely that the designs of many satellites will follow the pattern set by the space telescope and that in a decade or so there will be a significant number of permanent facilities of this kind in near-earth orbit. Once this happens, there will come a time when it will be more convenient (and probably less expensive) to have an operating base in earth orbit for the conduct of replenishment and refurbishment missions. The cost-effectiveness calculation cannot yet be made with any precision, but there is clearly some critical number of satellites above which the cost of making a trip from the earth each time a refurbishment operation is carried out exceeds the investment necessary to build a space station. The space station would also be extremely useful as a facility at which large space structures can be assembled. There is every reason to believe that such structures will become very important as we deploy large antennas in geosynchronous orbit for direct broadcast satellites or large mirrors for improved light-gathering power. In addition to the construction operations, manufacturing procedures of the kind described above in this section would benefit from a permanent space station.

Finally—and this is perhaps the most important point—the space station will become the staging base for other future missions. It is probably not possible, for example, to perform a manned planetary mission without having a staging base of the kind provided by a space station. Also, at some time, people will want to return to the moon, and if we wish to carry out sophisticated operations there, a staging base in earth orbit is required. The technical argument is quite simple: putting people on other planets and conducting significant operations on the moon require the existence of "true" spaceships—that is, vehicles designed to fly in space. The only true manned spaceship that the United States has ever developed is the lunar excursion module. All others—the rockets, the Mercury, Gemini, and Apollo capsules, and, of course, the shuttle itself—are hybrids; that is, they are designed to fly both in space and in the atmosphere. The heat shields and the control surfaces that must be added put prohibitive weight penalties on these vehicles if, for example, a shuttle flight to the moon and back is contemplated. The right way to put significant payloads on the moon is not by using only the shuttle, but by transferring the payload from the shuttle to a true spaceship at the orbital staging base (the space station) and then going on from there.

Although all of the things that will be done with a space station are important, it would be a mistake to ignore the space station's symbolic political value. The President recognized this point explicitly when he proposed the construction of a space station. He understands that a vital function of political leadership is to provide visions for the future, and he clearly views the space station as such. There is every reason to believe that the space station will attract considerable public attention and therefore have value beyond the practical utility that has just been discussed. Furthermore, we have strong evidence that the political leaders of our allies feel the same way. NASA administrator James M. Beggs recently completed a visit to European (German, French, Italian, and British) and Japanese political leaders to initiate the discussions that will lead to the collaborative effort that President Reagan has in mind. The response of the foreign leaders was enthusiastic, and there is no doubt that the nations they represent will make very important contributions to the space station program (O'Leary, 1983).

For all these reasons, the space station is the next logical step for the enterprise in space. Thus, in the coming years the United States and its allies will begin the construction of a permanent space station to, as President Reagan put it in a speech on July 4, 1982, "exploit the potential of the shuttle to establish a more permanent presence in space."

VISIONS FOR THE FUTURE

What lies ahead in aerospace? What predictions can be made with relative safety, and are there some surprises in store? In the preceding sections, some of the nearer-term plans and possibilities have been described in some detail. It might be worthwhile, therefore, to attempt a look a little further into the future to try and define some things that can only be dimly perceived today. I recognize that I am taking some risk in doing this, but I cannot resist the temptation.

We now have an air transportation system that, despite some economic problems, is extremely efficient when it comes to transporting people and goods over stage lengths in excess of 500 miles. It is unlikely that a new technology will lead to changes that will improve what has come to be called the long-haul air transportation system by an order of magnitude. Improvements will be evolutionary and substantial, but not earthshaking. The interesting question is whether there is room for some revolutionary change in some other part of the airline business. One of the really significant changes that was brought about by the deregulation of the airlines in 1978 is the growth of commuter, or short-haul, airlines. These airlines serve a market centered on smaller cities that are no longer served by major carriers. They use small, inexpensive turboprop aircraft to provide this service. Interestingly, most of the aircraft operated by the commuter airlines today are of foreign manufacture (the De Havilland DH-7, the De Havilland Twin Otter, the Shorts Skyvan, and others), primarily because American manufacturers felt that there was no market for these airplanes.

Is there a chance that American manufacturers can recapture the commuter market through the application of new technology? If so, what must be done to achieve this objective? There is, I believe, a good chance that a new technology that might be very useful is the tilt-rotor, vertical-takeoff-and-landing (VTOL) airplane. These airplanes can take off vertically, like helicopters, using two large rotors mounted on the wingtips of the aircraft. Once off the ground, the rotors are tilted forward, and they become the propellers of a more or less conventional airplane that can travel at 350 knots—over twice the speed of a conventional helicopter—without the severe vibrations that make helicopters very expensive to operate. A joint NASA-U.S. Army program that was executed during the 1970s resulted in the development of the Bell XV-15, an experimental tilt-rotor airplane. Two aircraft were built and have been thoroughly tested. Their performance exceeded original expectations. There is no doubt that a larger version of the XV-15 would be an excellent commuter aircraft. The VTOL feature of the airplane could have a very profound effect on airline service, because it would, for the first time, make airlines—or at least the commuter airlines—independent of airport facilities. Application of tilt-rotor airplanes in this way might lead to the first true "airbus" service (Civil Aviation, 1971).

What must be done to bring tilt-rotor airplanes into the commerical service envisioned here? It is possible, even likely, that the development of tilt-rotor airplanes will follow the pattern we have already seen in the case of the large multiengine jet aircraft. The military has initiated a program, called JVX, with the objective of replacing the large troop-carrying helicopters used by the Marine Corps. A decision has been made to use tilt-rotor technology for this purpose and to develop a relatively large (40,000 pounds gross weight) tilt-rotor airplane. There is good reason to believe that once these airplanes go into service, we will learn enough about the economics of operation and the technical maintenance and safety problems that the aircraft can be put into commercial service with relatively low risk. There is a reasonable chance that we will see this development in the coming decade.

The VTOL principle will have other military applications in the future when applied to high-performance aircraft. The British Harrier and the McDonnell Douglas AV-8B, which is a derivative of the Harrier, are examples. Some advanced VTOL concepts are under development that would ultimately be more efficient than the Harrier with its vectored-thrust propulsion system. The importance of high-performance VTOL combat aircraft is intimately linked to air base survivability. These airplanes will be developed with great urgency if we are ever forced to fight a war in which our major operational bases come under attack. The two major conflicts in which the United States has been involved since the end of World War II (Korea and Vietnam) were both fought under political ground rules that permitted our tactical air forces to operate from air bases that were treated as sanctuaries. Thus, the problem of dealing with air base survivability has not really been uppermost in the minds of senior air force people. Once this changes—and I think that it will—high-performance VTOL combat aircraft will be developed.

In addition, there are possibilities for the longer term that should be mentioned. Some people are thinking about transport aircraft that may be twice as large as the current Boeing 747s and Lockheed C-5As. These would have a gross weight on the order of 1.5 million pounds and would of course have enormous range-payload capabilities. One of the intriguing possibilities that may become practical for aircraft of this size is the use of liquid hydrogen as fuel. This could lead to a substantially higher propulsion efficiency and a new plateau of performance. There are also ideas for very-high-speed (above Mach 5) aircraft that might be used for various purposes, but these are only in the planning stage. What is important is that the aeronautical community has no lack of bold ideas and that some of these will eventually come to fruition and see practical application.

I have already described in some detail the things that can be expected to happen in space operations and space technology. Sometime in the next few years, the United States will build a permanent space station that will be used as a staging base for more ambitious operations. Sometime before the end of the century, people will return to the moon and establish a permanent base. In the next few years, the first steps will be taken to deploy a working ballistic missile defense system based on the latest developments in aerospace technology. There is not much question that the existence of such a system will change the framework in which international politics are conducted. We must begin now to think through the implications and to imagine the kinds of alliances and relationships that we will want to create in a world that can no longer rely on the nuclear balance of terror to maintain stability. It is at least possible to imagine an era in which stability and peace are preserved by a space-based complex of sensors, communications systems, and weapons, in much the same way that stability was preserved by the deployment of nuclear weapons systems in the past 40 years.

Although all of this is extremely important, I would be remiss if I did not talk about science, which is, after all, the cutting edge of understanding. In 2 years, we will launch the space telescope, which will be, by any measure, the most important scientific instrument ever flown in space. What will we learn when we point the space telescope at the stars? We already have strong hints that the extremely energetic processes we see in quasars and pulsars have to do with entirely new states of matter that contain, in a more or less thermal equilibrium state, the particles we observe on earth only in very high-energy collisions produced in high-energy particle accelerators. It is quite possible that by combining the information we obtain from the space telescope and high-energy accelerators, we will be able to achieve Albert Einstein's dream of a unified field theory of forces. This theory would include the entire array of forces known in nature—from the gravity that governs the motions of galaxies to the forces between the subnuclear particles we call quarks. Once this edifice is built, I am sure that there will come practical applications, just as we saw extremely important applications come from Newton's unification of the work of Kepler and Galileo (Mark, 1983).

An observation that may ultimately be even more important will become possible with the space telescope. We will, for the first time, be able to establish with certainty whether there are other stars that have planets orbiting them. There is good reason to believe that such planetary systems as the one that accompanies our sun are fairly common. If this point can be established, then the next task, of course, will be to determine whether there are planets around other stars in the galaxy on which the phenomenon we call life has occurred. Are we alone in the universe? Is life unique or is it common? These are obviously all questions of the highest importance, and the space telescope will begin to provide us with the first answers. Answers to questions of this kind will obviously have profound philosophical and political implications. If the evidence mounts that we are alone, then that will influence the way we think about ourselves. On the other hand, if we discover that we have companions elsewhere in the universe, then a different set of consequences will follow. Whatever happens, as Professor Philip Morrison has said, the possible outcomes boggle the mind (Billingham, 1979).

I started this paper by asserting that aerospace is a peculiarly American enterprise. In closing, I want to return to this theme. The United States stands for progress, and there is no doubt that we have made great progress in adding to human knowledge and well-being by the application of aerospace technology. The United States stands for peace, and it is clear that the application of aerospace technology has helped maintain the precarious peace that exists in the world. Above all, the United States stands for freedom, and this is perhaps the area where the contributions of aerospace technology have been most significant. We have provided the freedom to move and travel on a worldwide basis so that millions can now see the world for themselves. Most important of all, we have expanded human horizons and challenged the imaginations of millions around the world through the new adventure of space travel. In doing so, we have reaffirmed our faith in the future, and this is ultimately what freedom is all about.

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Materials Sector Profile

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MATERIALS SCIENCE AND ENGINEERING as a field of inquiry has undergone a fundamental and dramatic change over the past 2 decades.

This paper reviews both the rapid rate of change in the materials sector's many subfields of materials science and technology and the public and international policy implications of the "revolutions" taking place in this sector. The paper also reviews the U.S. government performance in response to the rate of change. Within this paper are two broad surveys: a technological survey and a policy survey.

The technological survey includes a description of the current status of the fields of materials science and engineering and projections of the rate of technological change in these fields over the next 20 years. These projections focus on three major economic segments: defense and space systems, transportation systems, and energy systems.

The policy survey focuses on the two major and interrelated origins for materials policy development at the federal level that now influence and will continue to influence foreign policy. The first is the transfer and management of materials technologies essential to the development and acquisition of advanced defense systems within the United States and among our world allies. The second deals with those policies that focus on strategic and critical materials essential to our national security and war-fighting capabilities under national emergency conditions. Included in this survey is a section that outlines the evolution of federal materials policy development over the past 30 years, the current structure within the administrative branch for policy development and implementation, and a chronology of performance under the Reagan administration. The section is intended to be a stimulus for new concepts for improving the national materials policy and program structure rather than a comprehensive survey and analysis.

STATUS

Materials Science in Transition

The change in materials science and engineering was characterized by William Baker and Morris Cohen in the 1975 Committee on the Survey of Materials Science and Engineering (COSMAT) report by the National Academy of Sciences (NAS) by the emergence of the science of the solid state as a field of major importance in the latter half of the twentieth century. Also contributing to this change was the joining of technologies from the ancient fields of metallurgy and ceramics with the contributions from the more current fields of synthetic polymers, rubbers, plastics, and modified bioorganic substances. To stimulate the exchange of ideas among experts in these fields and to accelerate development of new materials, the Defense Advanced Research Projects Agency of the Department of Defense (DOD) established several interdisciplinary laboratories in materials sciences and engineering 2 decades ago at major American universities. Since then, these materials research laboratories have had a significant influence in unifying the subfields of materials science at universities. The support of such laboratories has been continued by the National Science Foundation (NSF).

Perhaps the most dramatic change has been a stronger systems orientation by the materials research community at large. The previous dominant focus on structure-property relationships has changed to a focus on greater integration of design, performance, and processing requirements with materials properties and microstructures. As a result, final microstructures can be tailored more rationally to specific applications. This change is most dramatically observed in large-scale integrated circuits, where, in addition to the circuit elements, materials structures and transport properties are intricately integrated.

In commercializing these developments, however, a higher order of functional integration involving still more disciplinary groupings, has been necessary. New requirements for materials performance and reliability have emerged not only from a gradual shift in societal values from a consumption to a conservation orientation but also from world competitive forces that place high marketing premiums on quality, reliability, and low operating and maintenance costs over the expected lifetime of the product. These marketing requirements have necessitated an extended technology base and detailed attention to a number of new technical-forcing functions. For example, the singular focus of Japanese manufacturers on building in quality and reliability through in-process controls rather than adding value to scrap has been a major factor in Japan's productivity gains. Productivity gains and cost advantages have been achieved by some American manufacturers by tailoring their processes to an optimal equipment design rather than insisting on customized equipment to accommodate an optimal process design. Advances in quantitative nondestructive evaluation have not only facilitated in-process inspection but also led to viable reworking and recycling strategies for high-value materials and components.

These developments have been further spurred by the advent of computer-aided design and manufacturing, which have presented to the design engineer both new flexibilities for materials use patterns and new opportunities for design optimization based on either new materials or improvements to existing materials. Artificial-intelligence-based systems are emerging to improve the quality of decision modeling and to reduce human error in production, inspection, and testing activities.

Contributions to materials science from collateral fields of physics and chemistry have provided an expanded base of knowledge and a greatly extended ability to study the structures of both crystalline and amorphous solids. The expanded use of particle accelerators, high-resolution electron microscopes and microprobe analyzers, intense-pulsed neutron sources, synchrotron light sources, surface analytical instruments, and optical probes to characterize the electronic, atomic, and molecular properties of condensed matter states have opened up new pathways for materials synthesis.

Materials as a National Imperative

As a result of dramatic technological developments over the past 2 decades, the discovery and development of new materials have become a national imperative for the United States and for our major world competitors and adversaries. The following are emerging requirements that are based on higher technological dimensions, and these higher dimensions will not be realized without new materials:

- As technologies in conventional industries are transferred to developing countries, it is inevitable that the United States change its industrial structure, based on new technology, to maintain current standards of living or to achieve further increases in per capita added value.
- Future energy developments require technologies that create conditions far beyond the conventional, such as ultralow temperature, ultrahigh temperature and pressure, supervacuum, ultrahigh magnetic fields, and ultra-intense and ultraenergetic radiation environments. Our future national security depends on new technologies to conserve and substitute for energy and other scarce resources.
- There is a growing search for higher accuracy at the atomic and molecular levels for new machining, measuring, and processing developments. This is especially being sought after in the DOD program in ultrasmall electronics research, which is attempting to extend electronic devices and circuit technologies to molecular dimensions (i.e., 10–20 nanometers).
- New public needs and demands for new life-styles are growing out of expectations from the information revolution.
- Technology is becoming increasingly essential as a major force multiplier in the development of new strategic and tactical weapons and battle management systems.

New Materials Developments

The fields of materials science and engineering are burgeoning—so much so, that it is difficult to distinguish between future developments and near-term applications. This can best be illustrated by reviewing the major materials developments identified in the 1979 NAS 5-year outlook report to NSF as those likely to have a major impact to society before the turn of the century: directional solidification of cobalt-base and nickel-base superalloys, single-crystal turbine blades, rapidly solidified superalloys, semiconductor infrared detectors, fiberoptic transmission, bubble memories for computers, synthetic polymers, silicon nitride and silicon carbide ceramics, high-performance resin-matrix and metal-matrix composites, precision investment casting, powder metallurgy consolidation techniques, laser treatment of surfaces, computer-aided design and manufacturing, and very-large-scale integrated-circuit silicon chips. Taken as a whole, this list represents technologies that have already been reduced to commercial practice and that will have a significant impact on society before the end of the decade, let alone the turn of the century.

A reflection of just a few of these developments will reveal the rapid rate of change in materials development:

- The last 2 decades have provided many notable advances in near-net-shape fabrication methods, advances that greatly reduce or in some cases eliminate the need for final machining or grinding operations. For example, turbine blades are now being produced by single-crystal castings, and complex shapes are being commercially produced by one-step, superplastic forging of powdered-metal billets.
- In just over a decade, the optical attenuation of silicon fibers has been reduced by over five orders of magnitude at selected wavelengths. Developments in optical materials and concurrent advances in semiconductors and electronically active polymers have brought about new developments in advanced sensors, control systems, inspection systems, medical diagnostics, microsurgery techniques, and communications.
- Advances in cutting tool materials are fulfilling needs for higher tool speeds and material removal rates. The availability of advanced ceramics, ceramic-metallic compacts, intermetallic compounds, and ceramic coatings has been a key enabling factor in the stepped-up activity in this field.
- Trends in polymers are at the forefront of future technologies. Commercial developments over the past 2 decades include polyamide fibers with strength and modulus properties superior to those of many materials commercially available today; temperature-resistant aromatic polymers that will displace many strategic metals* for elevated temperature applications; electronically active polymers with electrical conductivities close to those of conventional metals; improved thermoplastic resins suitable for stamping out high-production-rate, fiber-reinforced composite parts; and polymer blends, alloys, and multicomponent structures with optimum combinations of properties.
- For transportation systems, the quest for new materials with

*Strategic materials are those needed to supply the military, industrial, and civilian needs of the United States during a national emergency and whose supplies are dependent on imports (e.g., chromium, cobalt, manganese, and platinum-group metals).

higher strength and stiffness relative to density has led to increasing use of composite materials consisting of reinforcing fibers of carbon, polymers, metals, and ceramics embedded in matrices of polymer resins, metals, and ceramics. Larger percentages of the structural weight of airframes for commercial and tactical aircraft are now being fabricated from graphite-reinforced plastics. Furthermore, these composites are increasingly used for helicopter rotors and propellers.

In addition, consider the following additional major materials-based developments that have also supported significant technological revolutions during this period:

- liquid crystal displays
- high-strength, low-alloy and microalloyed steels for automotive use
- fast-ion-transport solid electrolytes and highly selective membranes for advanced batteries, fuel cells, and potentiometric gauges*
- more efficient photovoltaic materials, such as single-crystal silicon ribbons, polycrystalline silicon, chemically modified amorphous silicon, III-V semiconductors, and thin-film homojunctions and heterojunctions
- physical vapor deposition and ion implantation processes for modifying surfaces and depositing unique coatings to achieve improved wear, fatigue and corrosion resistance, optical properties, and conducting layers on dielectric substrates
- high-efficiency, carrier-injection, electroluminescent materials
- nonlinear polymers that have order-of-magnitude improvements in electro-optic properties over inorganic compounds
- toughened ceramics that resist crack propagation by using crack-induced transformation of dispersed phases or by highly dispersed lattice discontinuities that serve as crack arrestors.

Although by no means all-inclusive, these dramatic materials contributions illustrate the swirl of research and development (R&D) activity in materials and the many technological frontiers on which materials scientists and engineers have been making significant advances.

*Instruments for measuring electromotive forces.

FORECAST

Rate of Change

Over the next 20 years, the demands, use patterns, and sources of materials can be expected to change dramatically. These changes will affect not only what materials are selected but also how they are processed, fabricated, assembled, used, and recycled. Among the various classes of materials, use patterns can be expected to change more rapidly for ceramics, polymers, composite materials, and amorphous materials—at the expense of the more conventional metals and alloys.

The demand for silicon for semiconductors will continue to increase over the next 10 years, but the demand for compound semiconductors will accelerate even more. Increasing use will be made of continuous steel processing, near-net-shape fabrication, higher-speed metal removal, novel methods of surface modification, rapid solidification, directed-energy and plasma processing, autonomous nondestructive testing, short-wavelength lithography, low-temperature deposition and epitaxial processes for thin films and heterojunctions, convection-controlled single-crystal growth, photon-activated chemical reactions, improved diffusion joints and adhesive joints between dissimilar materials, dynamic compaction of metal and ceramic powders, and other processing advances. All of these will contribute to improved quality and productivity.

Some examples of changing materials use patterns in defense and space systems, transportation systems, and energy systems will illustrate a few rates of change that can also have major impacts on society, on industrial economics, and even on government policies.

Defense and Space Systems

Advanced Superalloy Systems Dramatic improvements in the past 10 years have been made in the specific thrust and specific fuel consumption of commercial and military jet engines. For example, turbine blade cooling flow has decreased from approximately 4.3 percent to 3.2 percent of core flow, and turbine inlet temperatures have increased by about 150° F. These improvements have been principally achieved by the introduction of directionally solidified superalloy turbine blades, intricate ceramic casting cores to define internal cooling passages, and improved aluminide coatings to provide oxidation and hot-corrosion resistance.

The dramatic rise in fuel costs over this same period has created competitive pressures and demands in the air transportation industry for reductions in engine weight, fuel consumption, and life-cycle costs. Many of these demands require radical changes in alloy development, processing technology, and design concepts. The development of single-crystal blade materials that promise temperature improvements of 75°–100° F over directionally solidified materials, represents one of these radical changes. By eliminating grain-boundary strengthening elements and by dissolving and reprecipitating the gamma-prime phase in these alloys, more effective use of precipitation strengthening and solid-solution strengthening can be used in their design.

The first commercial engine using single-crystal turbine blades—namely, Pratt and Whitney's JT9D-7R4 turbofan for wide-body commercial transports—is already in production. Current plans call for single-crystal turbine blades coated with aluminides to go into production for the Pratt and Whitney F100 military engine starting in 1986. Between 1990 and 2000, single-crystal blades will see expanded use for nonman-rated engines, such as those for the Advanced Strategic Cruise Missile, the Advanced Strategic Intercontinental Cruise Missile, and the Medium-range Air-Surface Missile.

Still higher temperature improvements will afford the designer much greater flexibility to trade off performance gains against major improvements in engine durability, fuel savings, and overall engine life-cycle costs. Moreover, these higher temperature improvements can be traded off for manifold improvements in engine durability. Improvements in cooling airflow requirements and in engine rotor speeds would result in increased specific thrust, decreased fuel consumption, and decreased engine weight. These gains translate into greater combat persistence and maneuverability, greater ordnance-carrying capacity without loss of fighting capability, increased range, and reduced infrared signatures. For example, with regard to the latter, a nonafterburning engine could be made with a specific thrust equivalent to current afterburning engines.

One of the new materials technologies of interest for high-temperature turbine blades is rapid-solidification technology, as applied to two-piece blades, radial-wafer blades, and rapid-solidification, plasma deposition blades. These blade forms are consolidated from rapidly solidified powders and are dynamically recrystallized into columnar grains or single crystals. Such RSR blades offer increased temperature capabilities over directionally solidified MAR-M200* of from 150°–400° F, or higher. They also offer a decreased use of strategic materials, such as chromium and cobalt, assuming that suitable internal and external protective coating systems can be developed for them. On the basis of current development schedules, however, it is unlikely that engines with RSR blades or vanes will enter service before 1990 (C. S. Kortovich, personal communication).

Directionally solidified eutectic (DSE) alloys,† strengthened by gamma-prime and reinforced with about 40-volume, percent-aligned TaC lamellae,‡ offer increased temperature capabilities of about 70°–200° F over directionally solidified MAR-M200 (Kortovich). Development needs for DSE alloys include methods to improve shear-rupture strength and thermal-fatigue resistance, to design a suitable root-joining technique, and to develop protective coatings with a strain-complient coefficient of thermal expansion. Because of uncertainties in fabrication costs, there is presently no projected schedule for the introduction of DSE blades for military engines.

Oxide-dispersion-strengthened (ODS) and fiber-reinforced superalloys (FRS) potentially offer use temperature increases of 300°–400° F over directionally solidified MAR-M200. The feasibility of fabricating a composite, hybrid blade from W-1%ThO_2-reinforced FeCrAlY§ at projected manufacturing costs competitive with directionally solidified blades has already been demonstrated (Kortovich). Such a blade would signal a significant use of long-range-ordered alloys for engine structural components other than protective coating systems. ODS alloys are already in production as the first-stage vane of the General Electric F-404 engine. However, the present stress states of current root attachment schemes present major limitations for ODS alloys. The use of ODS and FRS materials for military and commercial turbine blades will probably not occur before the early 1990s.

The evolution of protective coatings for turbine blades and vanes

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*A commercial nickel-base superalloy.

†The eutectic reaction involves the coexistence of two solid phases in equilibrium during the solidification of a liquid solution.

‡Thin plates of the compound TaC, which crystallize with a high length-to-thickness ratio during solidification from the melt.

§W-1%ThO_2 is a reinforcing fiber of tungsten containing highly dispersed particles of ThO_2 to impede grain growth. FeCrAlY is an intermetallic compound of iron, chromium, aluminum, and yttrium that has good oxidation and hot-corrosion (sulfidation) resistance.

will be driven by the need to provide greater oxidation and hot-corrosion protection as use temperatures increase. The likely trend during the 1980s will be from aluminide to platinum-aluminide coatings to overlay coatings. Thermal barrier coatings, based on partially stabilized zirconias, will emerge during the late 1980s and beyond. Thermal barrier coatings will allow a further decrease in the airflow in hollow, air-cooled blades and will increase the use temperature by an additional 30° F per 100 micrometers of thickness (Sprague, 1982).

The most immediate development problems for coatings are in overcoming negative effects of defects in the coating layer on the low-cycle fatigue life of the substrate material. The challenge will be to develop thinner coatings, gradient-layer coatings, and more forgivable coatings that will stand up to the extreme temperature cycles of advanced, high-performance engines.

Advances in turbine and compressor disk materials in recent years have been due primarily to improvements in powder metallurgy technology and to alloy design advances that permit higher additions of hardening elements, such as aluminum, titanium, molybdenum, tungsten, and columbium to achieve higher tensile, creep, and fatigue properties (Sprague, 1982). These advances have contributed to increased rotor speeds, higher cycle/pressure ratios, and greater engine durability. Future advancements will be primarily through processing technologies that will lead to hybrid disks and integrally bladed disks. The hybrid disk has tailored microstructural and compositional variations across the disk radius to meet the different property requirements at the disk bore and at the disk rim. The integrally bladed disk, or "blisk," is currently under development for small engines. Again, unique fabrication techniques are needed for blisks to tailor the properties at the hub and blade regions to meet specific design requirements.

Many of the materials and processing developments being pursued for advanced military and commercial jet engines are also of interest for rocket engine turbomachinery, for example, high-pressure fuel turbopumps used for space shuttles. Because of the high premiums tied to weight reductions in such space propulsion systems, the application of long-range-ordered alloys, such as titanium aluminide, which exhibits high specific modulus, high specific creep strength, and good oxidation resistance at elevated temperatures, looks especially attractive.

Advanced superalloy systems—along with refractory alloys, cermets,* metal matrix and ceramic matrix composites, and long-range-ordered alloys—have high interest for space power systems involving compact nuclear reactors and in-core thermionic conversion systems, which would typically operate in the range of about 800°–1,250° C. Again, because weight is an important design parameter, advanced composites and long-range-ordered alloys would be of interest for core components, radiators, pumps, manifolds, piping, and structural supports.

Advanced high-temperature alloys, metal matrix composites, intermetallic compounds, and high-temperature protective coatings are also in demand for defense high-power laser systems. Critical components include laser nozzles, manifolds, mirror substrates, mirror heat exchangers, and heat rejection radiators.

Other Advanced Materials

Other classes of advanced materials will also be introduced into defense and space systems during the next 20 years. By 1990, advanced structural ceramics, such as silicon carbide, silicon nitride, silicon-aluminum-oxynitride (SiAlON), stabilized zirconia, and toughened multicomponent, multiphase ceramics will find increased use for heat engine applications, gun barrel liners, and wear and impact parts, such as bearings. Uncooled, turbocompound engines with thermal efficiencies of 48 percent and ratings ranging from 450 to 750 horsepower (hp) will have been demonstrated (Bryzik and Kamo, 1983). These engines will use ceramics for pistons, cylinder heads, valves, cylinder liners, exhaust valves, and exhaust ports. Vehicle implementation will be under way for heavy trucks (15–30 tons) and for tracked combat vehicles. Developments for 1,500–2,000-hp power plants for main battle tanks will also be under way. Finally, special optical ceramics that can provide both a broader spectral band pass and improved aerothermodynamic protection for supersonic missile radomes and infrared domes will see expanded use.

The next generation of rotary aircraft, now in advanced development, will have primary structures—roof structure, fuselage, boom, rotors, and aft rotor drive shaft—constructed almost entirely of advanced epoxy composites reinforced with various combinations of

*Strong alloys of a heat-resistant compound and a metal.

graphite, glass fibers, and DuPont Kevlar (Av. Week and Space Tech., 1984). These composite structures will provide more weight savings per aircraft (up to 1,000 lbs), greater tolerance to ballistic damage, lower radar cross sections, and better crash worthiness. Advanced epoxy composites will also be used more extensively in tactical and transport aircraft. New self-healing coatings, hydrophobic adhesive bonds, and improved repair and nondestructive evaluation techniques will greatly extend polymer composite life.

During the 1990s, carbon-carbon and metal matrix composites will displace epoxy composites, superalloys, beryllium alloys, and more conventional alloys for special applications. In addition to current uses for ballistic missile reentry body nose tips and rocket engine nozzle throats, carbon-carbon composites show high potential for use as turbine blades and other hot-section components for cruise missile engines. Metal matrix composites will find uses for turbine and compressor components for advanced aircraft engines; for spacecraft instrument benches, trusses, radar antennae and antenna booms; for heat exchangers to cool high-energy laser mirrors; and for a variety of missile and aircraft structural components. The higher costs of these composites will be offset by improvements in vibration damping, radar absorption, and weight reduction, as well as by increases in payloads, range extension, and thermal-structural stability.

Emerging materials processing and coating methods (such as rapid solidification and laser surface treatments) will extend the lifetime of military hardware subjected to extreme corrosion and wear environments. Considerable improvements will also result from the greater application, facilitated by computerized data bases, of existing knowledge of corrosion and oxidation protection techniques. New alloys developed from rapid-solidification and dispersion-hardening technologies will include aluminum alloys having the strength of steel. These new aluminum alloys will find increased use in high-mobility vehicles requiring a degree of ballistic protection.

Active, highly nonlinear polymer films will find important defense and space applications over the next 20 years; for example, in integrated microelectronic, microelectro-optic, and magnetic circuits; thin-film infrared sensors; lithographic resists; electro-optical filters for the protection of optics; high-sensitivity acoustic and seismic sensors; and high-density computer memories. For many of these applications, such polymer films will be used in conjunction with inorganic semiconductors in microelectronic circuits.

Transportation Systems

The automotive industry is already experiencing a materials revolution with the increased use of high-strength steels, fiber-reinforced composites, structural polymers, and high-technology ceramics to meet fuel economy goals. As pointed out by Harwood and Layman (1983): "By the mid-1980s, the average vehicle will weigh under 3000 lbs. While still comprised of 50% steel, some 150 lbs. of aluminum, 350–400 lbs. of new grades of high-strength steels, and some 250 lbs. of plastics per car will be used. As compared to the late 1970s, the use of grey cast iron will be decreased by about 40–50%."

The development of "dual-phase" steels, which have improved strength and stretch formability over conventional high-strength, low-alloy steels, has been a major factor in reducing the weight of automobiles and in fending off the encroachment of aluminum alloys in vehicle downsizing programs. The principal advantage of dual-phase steel is to optimize the strength advantages of hard constituents in steel (martensite or lower bainite) and offset their less desirable features with a softer second phase (ferrite). The overall mechanical behavior of the dual-phase steel is critically determined by the volume fraction, size, shape, and distribution of the stronger phase. Further optimization of duplex steels, in which processing advances will replace expensive alloying additions, will further economize on the use of strategic materials by the automotive industry.

Japanese automakers are already introducing high-technology ceramics in automotive heat engines in the form of pushrods, glow plugs, turbocharger rotors, swirl chambers, tappets, and seals. They plan to introduce new ceramic engine components annually throughout the remainder of the 1980s and 1990s until they achieve a fully integrated turbocompounded diesel engine, well before the year 2000. In addition to the race for the adiabatic engine, automakers and engine manufacturers in the United States, Europe, and Japan are actively exploring the use of high-technology ceramics parts for automotive turbine engines, regenerators, Stirling engines, Wankel engines, and aircraft auxiliary power units. In addition, functional ceramics will be increasingly used for electronic packages, sensors and probes, actuators, capacitors, thermistors, varistors for flat-panel displays, and auxiliary motor magnets.

The future is also bright for the use of polymeric materials in transportation systems. For example, bumper systems employing reaction-injection-molded urethane fascias are already familiar, and new bumper systems employing injection-molded blends of polycarbonate and polyester to form a "toughened" polymer alloy (General Electric Company's Xenoy) are currently being introduced in the United States and Europe. These new bumper systems will offer an 8-lb weight savings over an unadorned, high-strength-steel bumper (Wrigley, 1983). Other applications of advanced polymers to automobiles will include the tires, structural components, paneling, upholstery, trim, battery, electrical distribution system, and electrical sensors and displays.

A new, imaginative automotive application of polymers is the development of a molded plastic engine by Polimotor Research (Schuon, 1983). Such an engine, based on the Ford four-cylinder, 2.3-liter design, contains 40 lb of fiber reinforcement, 60 lb of resin, and 68 lb of metal, for a total weight of 168 lb. Starting in 1984, Polimotor will produce lightweight power plants (which can turn safely at 14,000 revolutions per minute and develop 318 hp) for racing cars. For current engines, the cost of carbureted and continuous fuel-injection systems can be significantly reduced by replacing aluminum and zinc castings with heat-stabilized, glass-reinforced and mineral-reinforced nylons and reinforced thermoplastic polyethylene terephthalate* (PET) polyesters.

Applications of thermoplastic resin composites in transportation systems are expected to increase over the next 20 years. However, their rate of introduction will depend primarily on cost reductions in materials and on advancements in automated, high-speed production methods.

Fiber-reinforced resin composites have been experimentally evaluated for many uses in the automotive industry. Glass-reinforced composites are already widely used in automobile bodies. Several potential applications have been identified for graphite fiber-reinforced and aramid fiber-reinforced resin composites, to include leaf springs, steering components, chassis components, and drive line components. However, fiber costs and the slow curing time and brittle nature of thermosetting resins are principal drawbacks. Thermoplastic resins—polyamide, polycarbonate, and thermoplastic polyester—are more

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*Made by a continuous process from ethylene glycol and terephthalic acid or its dimethyl ester.

amenable to high-rate production but generally have low strength and low maximum service temperatures. Specialty resins, such as polyetheretherketone and polyetherimide, contain stiff polymer chains and, as a result, have higher strength and higher maximum service temperatures (up to about 200° C). However, they are generally more costly and more difficult to process than the more common varieties.

The use of graphite-reinforced and DuPont Kevlar-reinforced epoxy composites in the fuselage, wing structure, seats, and other structures of commercial aircraft will increase over the next 20 years as more fuel-efficient designs evolve. Higher strength-to-density aluminum alloy sheet and extruded forms produced from rapidly solidified powders will also contribute to weight savings. The introduction of metal matrix composites and intermetallic alloys (e.g., titanium aluminides) for compressor blades, of directionally solidified and single-crystal, nickel-base superalloys for turbine blades, and of silicon-silicon carbide and carbon-carbon composites and covalent-compound ceramics for combustor components will result in greater weight savings, specific thrust, and conservation of strategic materials in advanced engine designs.

Energy Systems

Extensive R&D will be invested in materials technology for energy systems over the next 20 years to improve the efficiency of conventional energy systems, acquire the technological base necessary to exploit the vast coal resources in the United States, continue to improve the efficiency and safety of existing light-water reactor systems, develop nonconventional and renewable sources of energy, and provide the pollution control devices that are so essential to environmentally acceptable use of fossil fuels.

Materials use patterns are expected to be relatively stable over this period for conventional fossil and nuclear energy conversion systems. Materials R&D investments for some new energy sources, such as fast-breeder reactors, thermonuclear fusion experimental reactors, and coal gasification and liquefaction systems, will be primarily for characterizing the detailed behavior of existing materials or modified existing materials in the stringent operating environments inherent to these systems. Nevertheless, there will be important needs and opportunities for new, advanced materials over this period.

Metals and Alloys

Modified austenitic stainless steels* are being optimized for use in first-wall structures for magnetically confined fusion systems. These will be backed up by efforts over the next 20 years to search for alternate alloys having better combinations of temperature capability and radiation resistance. Such alternates will include iron-chromium-nickel superalloys, reactive and refractory metals and alloys, and new concepts, such as iron-base and cobalt-base long-range-ordered alloys, rapidly solidified alloys, graded materials, composites, and ceramics. Vanadium alloys look particularly attractive as an alternative to austenitic stainless steel because of their low neutron activation, temperature resistance, and resistance to helium embrittlement. However, because of the growing data base on the irradiation performance of austenitic stainless steels being generated from existing liquid-metal fast-breeder reactors and because of the extensive engineering resources needed for early development of demonstration fusion reactors, only the austenitic stainless steels are expected to approach optimization before the year 2000.

Other major efforts on metal alloy systems will focus on the following:

- structural steels with reduced susceptibility to hydrogen embrittlement and attack for hydrogen storage systems, Stirling engine receivers, and large pressure vessels for second-generation coal conversion systems
- improved wear-resistant materials and coatings for coal conversion systems, coal slurry pipelines, geothermal drilling tools, and direct-cycle gas turbine components and heat exchangers
- alloys that will withstand the corrosive attack of coal liquids; magnetohydrodynamic (MHD) seed recovery processes;† vanadium-containing, sulfur-containing, and sodium-containing petroleum fuels; geothermal fluids; and molten-salt, heat transfer, and storage media fluids for solar conversion systems.

*An iron-base alloy containing nominally 18 percent chromium and 8 percent nickel and for which the addition of nickel stabilizes the high-temperature austenite phase (face-centered cubic crystal structure) at room temperature.

†A chemical process for recovering seed elements, such as cesium, that have a low ionization potential in gaseous form and that are added to combustion gases to promote the formation of a plasma in an MHD generator.

Amorphous, "glassy" metals, solidified at rates of 10^5–10^6 degrees per second into strips several centimeters wide, will increasingly replace iron-silicon alloy sheets in electric power transformers. Low-cost, efficient household power transformers will become widespread owing to this technology. Glassy metals will also be used in energy systems as reinforcing fibers in structural composites and in novel structural forms and overlays, where their unique strength and resistance to corrosion and wear can be exploited.

Magnetic Materials

Cobalt-samarium alloys and ceramic ferrites will be displaced by newer rare-earth magnetic alloys that have higher magnetic energy products and lower costs. These new magnetic materials will significantly reduce the size and power requirements of auxiliary motors for automobiles and consumer products as well as of traction motors in transportation systems.

Conductors

For some electrical transmission systems, metal conducting cables could be replaced by lighter-weight and stronger cables based on intercalated graphite. Among the superconductors, NbTi,* the only truly commercial superconductor today, could be extended in use for magnets from 8 to 12 Tesla with further optimization (Department of Energy, 1978). However, Nb_3Sn† holds the greatest promise for producing fields from 12 to 15 Tesla. Higher magnetic fields will require such options as V_3Ga, NbGe, NbSi,‡ and new superconductors made of composite materials. Such high-field materials will require several more years of development to carry them through the manufacturing stage.

Ceramics

The future of high-technology ceramics in energy systems is extremely bright. In addition to the advanced heat engine applications identified earlier, a variety of insulators and structural ceramics will be required in fusion reactors for neutral beam injector insulators, insulators for radio frequency heating systems, low-Z first walls and lin-

*An alloy containing niobium and titanium.

†An intermetallic compound of niobium and tin.

‡Various binary and pseudo binary intermetallic compounds that exhibit superconductivity above 10°K.

ers, mirror direct converter insulators, tokamak current breakers, and insulators for magnetic coils (Department of Energy, 1978). Other critical applications for high-technology ceramics will include β-alumina separators for fuel cells and sodium-sulfur batteries, ceramics for electric resistance-charged heat storage units, silicon-based ceramic recuperators and hot-section components for high-temperature stationary gas turbines, cermets for high-performance selective solar absorbers, refractory liners for coal gasifiers, MHD electrodes, interelectrode insulators, and air preheater refractories, ceramic forms of nuclear wastes, and ceramic and intermetallic protective and thermal barrier coatings for gas turbine and diesel engine combustion zone components.

Special Glasses

Special glasses are under development for inertially confined fusion systems, to include laser amplifiers, Faraday rotators, laser windows, optical coatings, heavy-metal/glass liner shells for targets, and open, low-density, open-lattice structures for deuterium and tritium containment. Another principal application of glasses will be as waste packaging materials for the long-term confinement of nuclear wastes.

Polymers and Epoxy Composites

The most extensive application of polymers in energy systems is expected to be for active and passive solar collector systems. Special polymer films will be used as metallized reflectors, selective-absorbing laminated sheets, Fresnel lenses,* and protective polymer coatings. Polymer structural forms and piping are already being used extensively for home and building solar collectors. Active polymers will also find uses as electrolytes for producing hydrogen by the electrolysis and photolysis of water and as low-cost photovoltaic semiconductors and optical circuit components. Other structural applications of polymers and polymer composites will be as flywheel rotors for mechanical energy storage, gas centrifuge rotors for uranium isotope separation, coatings and containment shells for laser and particle-beam targets for inertially confined fusion, polymer concrete pipe used in the completion of geothermal wells, and fluorocarbon elasto-

*A Fresnel lens consists of a concentric series of relatively small sections of mirrors or prisms, making possible the thin lens with a short focal length and large diameter found in beam projectors.

mers for seals and for logging cable insulators in low-temperature geothermal wells.

Semiconductors

The growth rate of solar energy semiconductor industries will probably depend more on oil and gas price increases and the rate at which the U.S. economy shifts away from oil and gas to a broader range of energy options over the next 20 years than on further technological advances. Efforts will continue for finding methods for producing low-cost, highly efficient solar cells for converting sunlight directly to electricity, however. Continued process improvements and cost reductions in producing thin-film, polycrystalline, silicon cells on low-cost substrates with efficiencies greater than 10 percent can be expected. Further progress can also be expected in improving the efficiency, purity, and defect-state passivation* of amorphous silicon cells.

The cost of producing solar cells from gallium arsenide for direct steam production from solar concentrators should drop significantly over the next 10 years, owing to higher-volume production for the electronic industry. However, such cells are not expected to be a significant source of energy production in this century. Developments will continue toward demonstrating the feasibility of emerging photovoltaic materials (e.g., zinc phosphide, cadmium telluride, tungsten diselenide) for high-efficiency, multijunction concentrator cells.

Solid-state semiconductor power devices based on silicon and gallium arsenide (at the highest frequencies) will continue to replace older electromechanical equipment because they give better performance at lower cost (National Academy of Sciences, 1979). Solid-state, integrated magnetic circuits will emerge for bidirectional direct current-alternating current conversion with near-zero efficiency loss and distortion. Elevated-temperature sensors and electronic circuits based on gallium arsenide and silicon carbide will be developed for use in digital process controllers and for down-hole sensing and signal processing in petroleum and geothermal wells. In concert with these developments, further improvements will be made on new packaging materials and dielectric structures to meet future requirements for electrical circuitry.

*A process that suppresses the ability of defects to trap or promote the recombination of electric charge carriers (electrons and electron holes) in semiconductors.

Sources of Influence and Strength

With the advent of new materials, new demands will be created for fabrication, compositing, and assembly tooling and inspection instrumentation. The design and characteristics of the materials being applied must be intimately linked with manufacturing tooling and methods of assembly, joining, and inspection. Since the development of new materials is highly dynamic, displacements and upheavals in materials use patterns can be expected, and these will provide an active spawning ground for new equipment, instrumentation, and machine tool industries.

Looking abroad, governments of highly developed countries have chosen to promote new materials technologies strongly because of the resultant benefits to the entire economy. For example, the Japan Ministry of International Trade and Industry (MITI) is currently working closely with industry to establish cooperative research programs in semiconductors, carbon fibers, advanced polymers, biomaterials, and high-technology ceramics.

Japan will continue to become superior to the United States in some materials technologies. For example, Japan has assumed world leadership in the production of ceramic chip carriers for microelectronic circuits and in the application of ceramics for cutting tools, automotive engines, a variety of industrial applications, and biomedical implants. The MITI program in fine ceramics is expected to strengthen Japan's world position further in these markets as well as in ceramics uses for chemical sensors, flat panel displays, and a wide range of electronic and electrical devices. Other materials technologies for which targeted investments have been identified to build Japan's industrial structure for the twenty-first century are high-performance polymer materials, amorphous metals, directionally solidified superalloys, and magnetic materials.

Japan has also become a dominant technological leader in high-quality semiconductors, synthetic gems, carbon fibers, and some speciality steels. Also notable is its strong market position in materials characterization instrumentation, advanced lithographic equipment, and physical vapor deposition systems. As a result of Japan's current strong materials technology position, U.S. industry will make greater efforts to enter into licensing and technology-sharing agreements with Japanese industry to remain competitive.

Other nations competing for world markets (for example, England, France, and West Germany) are finding effective ways to use new technology as a competitive force. These nations (including the United States) are pursuing government interventions in the economy in ways that recognize competitive imperatives in the global marketplace, target the development of new industries, and provide incentives for closer cooperation among universities, industry, and federally funded research institutions.

The short-term and long-term economic implications for key industries are also being considered by these nations in the modification of programs and policies for taxes, antitrust barriers, regulations, education and training, infrastructure support, research, licenses, technology transfers, patents, government purchases, export financing, direct-export marketing support, and import standards and restrictions. U.S. policy machinery will have to be substantially modernized if U.S. technology is to remain at the cutting edge and if high-technology materials vital to our national defense interests are to be available in time of need.

FUTURE IMPACT ON INTERNATIONAL PROBLEMS

Military-Civilian Interface

One of the pervasive objectives of our defense modernization policy and program over many years has been to use technology, wherever possible, as a force-multiplier. Recently, because of rising acquisition, training, and maintenance costs, stepped-up efforts are being made to use new technologies to achieve simple and affordable—rather than complex and costly—military systems. This latter thrust has partially justified increased investments in manufacturing technology, microelectronics, robotics, artificial intelligence, simulators, advanced sensors, automatic fire control systems, and advanced propulsion systems, among others. These policies have also been major drivers in developing new materials. Consequently, DOD programs in structural and electronic materials have been growing significantly over the past decade relative to those in other technologies.

Many materials developments that have enabled dramatic advances in military systems have originated in the civilian sector, although major investments in their R&D have been made by DOD. These include a wide range of biomedical implant materials; oriented polyamide and various graphite fibers for composite structures; II-VI compounds and chalcogenide* glasses for laser optics, night vision devices, and mosaic infrared sensor arrays; ternary and quaternary lattice-matched III-V compounds for specific-band-pass, electro-optic devices; improved perovskite compounds† for nonlinear optical and acoustic sensors; high-yield-strength steels and titanium alloys for submarine hulls; intermetallic compounds and ceramics for lightweight armor; glass and polymer optical waveguide materials; rare-earth-transition metal and ceramic-ferrite materials for higher-efficiency microwave transmitters, guidance controls, and power management systems; compound semiconductors for millimeter-wave radar amplifiers; and many others. Some materials have become viable for commercial application only after pioneering, DOD-sponsored research. Such materials include artificial skin, covalent-compound ceramics for heat engine applications, nickel-titanium memory alloys, cubic-boron-nitride cutting materials, high-strength coated waveguides, fiber-optic sensors, and antireflective optical coatings, among many others.

The principal mechanism for materials technology transfer between the military and civilian sectors has been independent R&D conducted by industry under defense contracting policies. To a large extent this is a two-way street since much of the design, analytical methods development, data base generation, testing methods development, and manufacturing technology required to apply new materials to defense systems is a shared investment. Directly funded programs that require close collaborative efforts between DOD laboratories and industry are another major mechanism. Other policy instruments that are designed to assist technology transfer both into and out of DOD include small business set-aside programs and technology transfer provisions under the Stevenson-Wydler Act. These latter policies generally have a much smaller comparative impact on the transfer of materials technologies.

Cooperation and coordination in the development of defense materials by allied countries are carried out within three long-established bodies: the Technical Cooperation Program among the major English-speaking countries (Great Britain, Canada, Australia, and New

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*Generally, a binary compound of the elements sulfur, selenium, and tellurium with a more electropositive element or radical.

†Specifically, the titanate of calcium, $CaTiO_3$, but also used generally to describe other titanate and zirconate materials, such as barium titanate.

Zealand), the Defense Research Group of the North Atlantic Treaty Organization (NATO), and the Advisory Group on Aeronautical Research and Development, also of NATO. Materials technology exchange activities in these bodies consist primarily of the testing and evaluation of materials in advanced development stages and reviews of state-of-the-art research. Cooperative research on new materials at the cutting edge of technology are generally carried out under special bilateral agreements with a defined quid pro quo.

Several emerging trends are erecting new barriers to the exchange of new materials technologies between the United States and its allies and the systematic introduction of these materials into advanced weapons systems designated for NATO use. One such barrier is the inclusion of several new materials technologies on the Militarily Critical Technologies List (MCTL). Such inclusions of structural and electronic materials are a relatively recent practice and attest to the dramatic improvements in weapons performance made possible by these materials. Efforts to bring about rationalization, standardization, and interoperability (RSI) of NATO weapons systems are most economically carried out in their early development stages rather than late in the acquisition cycle. Judicious administration of the MCTL is required to guard against thwarting RSI initiatives in the early stages of weapons design.

A second barrier pertains to declining future opportunities for coproduction and offset agreements tied to foreign military sales of U.S. weapons systems as more sophisticated materials technologies are employed. Many new materials require specialized machining, forming, and handling equipment. Examples include hot-isostatic autoclaves for densifying covalent-compound ceramics (e.g., silicon carbide and silicon nitride); specialized weaving, lay-up, handling, autoclave, and inspection equipment for fabricating composite materials; and special isothermal presses and dies for forging titanium alloys and superalloys. Trends toward a greater use of near-net-shape fabrication, computer-aided machine tools, and customized robots also reduce the number of production operations that can be accomplished cost-effectively by conventional fabrication and machine shops. Therefore, countries that will be best able to participate in coproduction and offset agreements in the future will be those (e.g., West Germany, Great Britain, France, Sweden, and Israel) that already have substantial and competitive industries for producing weapons systems, high-technology materials, and machine tools. Japan, which also has these capabilities, will most likely continue to focus its capabilities on commercial rather than defense markets in the near term.

As a result of these trends, some NATO countries may choose to accept greater dependency on the United States for high-technology weapons systems rather than retain the heavy economic burden of an indigenous weapons research, development, and production base. Great Britain, for one, appears to be adjusting to such a policy.

A third barrier is related to critical and strategic materials, but not to those in the strategic stockpile (cobalt, chromium, manganese, platinum-group metals, and others, as is the common usage of that term). Stockpile materials are primarily an economic issue to DOD because of the several policy, supply, and technological options that can be applied in the event of a national emergency. The concern now, however, is over the growing U.S. dependence on foreign sources for high-technology materials, such as optical and structural fibers, fine ceramics, magnetic materials, high-quality semiconductors, and speciality steels. The United States is falling behind its world trading partners in several of these defense-critical, high-technology materials markets, and the expected trend is toward greater interdependence as a result of major, focused investments in these technologies by Japan, West Germany, France, and Great Britain.

The barriers described above relate to a growing interdependence among Western developed nations for high-technology materials and an increasing intertwining of both military and civilian uses of these materials throughout the world. For example, carbon-carbon composites used for intercontinental ballistic missile nose cones are also of interest for turbine blades in gas turbine power stations; metal matrix composites used in missiles, satellites, and high-power lasers are now in use for automotive engine valves and for commercial aircraft structures; graphite-epoxy composites used in tactical aircraft structures are also in use for commercial aircraft; rapid-solidification technology is being ubiquitously applied to a wide variety of commercial crystalline and amorphous materials; and covalent compound ceramics developed for military turbine and diesel compound engines are now in use for commercial automotive turbochargers and combustion systems.

Weapons production capability gaps that currently exist between upper-technology-tier and lower-technology-tier NATO countries are likely to increase rather than decrease because of intensifying international economic competition. Strategies to overcome the barriers described will require enlightened leadership and an environment of trust among NATO R&D communities and foreign policymakers.

Strategic Materials

Much has been written recently about whether or not the United States and the rest of the free world is in a "resource war" with the Soviet Union for those critical nonfuel minerals essential to our industrial base. Furthermore, enough has been written on our import dependence for these materials that it should be clear by now to every citizen that (1) mineral resources are not equitably distributed over the face of the earth, (2) it is neither geologically nor economically feasible for the United States to be totally self-sufficient in domestic resources for all key minerals, and (3) the disciplines of risk analysis and risk management are essential if we are to delineate between undue vulnerability and manageable dependency.

Such risk analysis must be specific to each individual strategic material in its own long-range supply-and-demand scenarios and must be based upon certain key operating assumptions about the seriousness of risks that must be either avoided or successfully managed. A few such assumptions, highly generalized but based on current persistent trends, are the following:

- The high-percentage import reliance of the United States for chromium, cobalt, tantalum, columbium, and platinium-group metals will continue until the turn of the century and beyond.
- The demand for most of these materials will increase at an annual rate of 2–3 percent to the year 2000.
- Domestic mining production, scrap recycling, and secondary recovery of tailings will probably supply only 10–15 percent of the U.S. demand for these materials under the best of potential circumstances, short of large-scale seabed manganese nodule and subsea polysulfide mining, dramatic technological breakthroughs, or a long-term supply cutoff that could marshal major investments in domestic production.
- The price of these materials will be susceptible to temporary supply disruptions, unreasonable price hikes, preemptive market manipulations, and source-nation political instabilities.
- Supplier countries will continue to invest in processing capacity and technology in order to benefit from the value added by refined materials, alloys, and mill forms. This trend will have the following

major impacts: (1) it will further displace the head end of our defense industrial base offshore; (2) it will render those raw or semiprocessed commodities in our strategic stockpile even more obsolete than they are today, since there will be neither the lead time nor the domestic capacity to convert them into the necessary defense production forms; and (3) it will also place more economic leverage into the hands of supplier countries, with prices of such materials continuing to seek new levels as dictated by supply control, speculation, and preemptive market maneuvers.

- International competitors of the United States will aggressively pursue a number of policies to secure their supplies of critical materials, to include geographically diversifying their sources of supply, acquiring direct production and distribution rights, and strengthening their relationships with resource-rich nations by supplying needed technology, production equipment, food, and other forms of economic and development aid.
- There will continue to be incentives for the Soviet Union to wage a resource war with the Western Alliance, since such a situation will put pressure on our allies to choose between the Soviet Union's long-term resources (or control of resources) and the United States' short-term stockpile and will provide a long-term hedge against a decline in economically available reserves in the Soviet Union relative to the Republic of South Africa for platinium-group metals, vanadium, manganese, and chromium.

Much remains to be done to improve the management of the strategic stockpile and to improve coordination among the federal departments in developing and implementing programs for nonfuel strategic materials. An example, based on changes in chromium supply and technology patterns over the past 2 decades, will illustrate why much of our current stockpile inventory is obsolete and should be discounted against currently established stockpile goals.

During the period 1956–1960 the United States provided 5–10 percent of its chromium needs through domestic production subsidized under the Defense Production Act. With the temporary termination of this act in 1961, the United States became totally dependent upon imports for chromite ore. Today the United States imports chromite ore primarily from six countries; South Africa supplies 44 percent of our chromite imports, and the Soviet Union and Albania together supply 30 percent (Congressional Research Service, 1982).

Before 1973, most of the ferrochromium required for the U.S. steel industry and other metallurgical applications was produced domestically. However, with the advent of the Organization of Petroleum Exporting Countries (OPEC) and the dramatic increase in oil prices in 1973, substantial ferrochromium production shifted offshore. The major economic factors underlying this shift were lower transportation costs, lower differential energy costs for ore processing, and the costs of U.S. environmental regulations. Whereas the United States produced nearly five times as much ferrochromium as it imported during the period 1970–1971, it now imports 20 percent more than it produces. The U.S. government now finds it necessary to take protective actions for both low-carbon and high-carbon ferrochromium because of declining prices for imported ferrochromium in the face of increasing costs of domestic production.

Concurrent with the dramatic rise in energy costs in the early 1970s, the introduction of the argon-oxygen decarburization (AOD) process further encouraged major chromite-producing countries to increase their ferrochromium production for export. This occurred because the AOD process permitted considerable interchangeability among various grades of ferrochromium. South Africa capitalized on this opportunity for an increasing metallurgical market for its low-grade ore by dramatically increasing productive capacity for high-carbon ferrochromium. As a result, the combined South African and Zimbabwean ferrochromium share of the world market has increased from 15 percent in 1970 to about 37 percent in 1979 (Department of Commerce, 1981). Together, these two African countries currently supply approximately 80 percent of total U.S.-imported ferrochromium (Congressional Research Service, 1982). It is important to note that as more of U.S. ferrochromium requirements are imported and as these imports become more concentrated from southern Africa, flexibility of chromite ore supply to the United States for metallurgical use, to include the contingent use of the United States' own domestic sources, will become more and more restricted.

As a result of these trends, the composition of our strategic stockpile is aligned neither with current technology nor with future national needs. Current stockpile goals for metallurgical-grade and chemical-grade chromite ores are about 15 times larger than those for high-carbon and low-carbon ferrochromium. This high ratio is inappropriate, considering that we now import more ferrochromium than we produce domestically. The goals for ferrochromium must be raised relative to those for chromite to reflect the decline in domestic ferrochromium capacity over the past decade. Also, those lots of ferrochromium in the strategic stockpile that contain sulfur levels higher than those which current steelmaking practice will accept must be rotated. Similar scenarios can be cited for other strategic materials in the stockpile.

U.S. GOVERNMENT RESPONSE

U.S. awareness of the importance of strategic minerals dates back at least a century; for example, the specific directive to Commodore Perry that his 1852–1854 Far East Naval Expedition explore for coal deposits; the Mining Law of 1872, which explicitly encouraged development of mineral resources of the public lands; or conclusions reported in 1886 by the Senate Select Committee on Ordnance and Warships, including the statement that "there has been more dependence upon foreign sources for manganese and the spiegel made therewith . . . ."

A true action program by the United States, let alone more forceful policy formulation, however, dates back less than the last 4 decades and was in great measure triggered by lessons learned in World War II and the Korean War. This program has included a sequence of legislation: the 1946 Strategic and Critical Materials Stockpiling Act; the 1953 Domestic Minerals Program Extension Act; the 1953 Domestic Minerals Program Extension Act; the 1956 Domestic Tungsten, Asbestos, Fluorspar, and Columbium-Titanium Act; and the 1970 Mining and Minerals Policy Act encouraging an economically sound minerals sector, including use and recycling of scrap and including energy resources within the definition of *minerals*.

The vulnerability of the United States today despite such strong statutory foundations, is fully explainable only through a more detailed historic narrative than that of this paper. Suffice it to state that the growing dependency of the United States on imported minerals subsequent to the passage of the 1970 act was due to a superposition of forces, including a serious erosion in U.S. mining and metals processing industries, stepped-up world competition, domestic mineral depletion, public land withdrawals, and expanding federal regulations. Legislative responses to severe fluctuations in defense stockpile scenarios, goals, and inventory disposals during the 1970s finally culminated in the enactment of The Strategic and Critical Materials Stock Piling Act of 1979.

This act provided that "the quantities of the materials stockpiled should be sufficient to sustain the United States for a period of not less than 3 years in the event of a national emergency." It also defined the terms *strategic*, *critical materials*, and *national emergency*. The other key provision of this act was its establishment of the National Defense Stockpile Transaction Fund, a strong step intended to preclude executive branch manipulation of the stockpile for federal budget balancing or economic policy purposes.

Subsequent legislation, the National Materials and Minerals Policy Research and Development Act of 1980, concluded that "the availability of materials is essential for national security, economic well-being, and industrial production" and found that "it is the continuing policy of the United States to promote an adequate and stable supply of materials necessary to maintain national economic well-being." Congress also declared that the principal directive and coordination authority in government for executing the provisions of the act should be the President, through the Executive Office of the President.

Since the passage of the 1980 act, congressional attention has focused on a variety of related issues, including mandating the Council on Critical Materials in the Executive Office of the President, nomination of promising public lands for minerals exploration by industry, multiyear extension of the Defense Production Act (DPA) and renewed application of its title III authorities for essential minerals development, providing private stockpiling options, taking the stockpile transaction fund off budget, and modifying barter provisions.

Materials policy issues for which federal governmental action is called are wide-ranging, from foreign trade and investment issues that can affect basic materials-producing industries to stronger R&D programs for all stages of the materials cycle. Some of these complex and intertwined policy issues and government responses are categorized below, followed by comments on selected government responses to these issues in recent years.

Policy Structure

Federal policy and implementation requirements and responsibilities are varied, but all fall under the headings of *risk analysis* and *risk management*.

Chief Executive Responsibilities

- Determine long-range materials goals for national security, basic industrial, and essential civilian services needs.

- Initiate the legislative and administrative measures necessary for establishing management structures and initiate the institutional programs necessary for achieving the goals of national materials policies and the strategic stockpile.
- Set budget priorities for programs necessary to assure the availability of materials critical to national security and the economy.
- Establish modes of management for U.S. materials preparedness and mobilization in case of national emergency.
- Direct and coordinate interagency policies and programs at the cabinet level.
- Establish early-warning systems for managing national security crises that could disrupt the supply of strategic materials.
- Conduct long-range assessments of materials needs and coordinate materials R&D, both federal and private, to meet those needs.

National Security

- Assess critical materials needs related to national security and identify the steps necessary to meet those needs.
- Develop a trioceanic strategy for the Indian, South Atlantic, and Pacific oceans in concert with allies to secure resource-bearing sea-lanes.
- Provide U.S. naval presence in critical sea-lanes.
- Establish defense priorities that take into account strategic material resource locations and security factors.
- Administer the DPA to ensure the availability of critical and strategic materials for weapons acquisition programs.
- Apply production stimulus through DPA title III subsidies, depletion allowances, and other forms of financial incentives to facilitate the development of domestic resources to meet critical materials needs that are essential to national defense.

Strategic Stockpile Management

- Enhance the adequacy of the strategic stockpile, qualitatively as well as quantitatively.
- Effectively apply the stockpile transaction fund and barter provisions for stockpile acquisitions.
- Sell excess materials to replenish the stockpile transaction fund without undue market disruption.

Foreign Policy

- Assess opportunities for the United States to promote cooperative multilateral and bilateral agreements for materials developments in foreign nations and to create investment opportunities that promote U.S. access to raw materials.

- Orient U.S. policies realistically with respect to nations that supply strategic minerals when U.S. import dependency upon those nations is unavoidable.
- Ensure the development of a law of the sea treaty that can provide for a positive and realistic economic and political climate for mining deep-seabed mineral resources.
- Consider strategic resource priorities in foreign aid programming.
- Promote diversity in foreign sources of supply to the extent economically and politically practicable.
- Establish a coherent, validly prioritized framework for private and government investments for exploration, development, and production of strategic minerals in developing countries.

Domestic Mineral Development Policy

- Inventory mineral reserves and potentials.
- Balance federal lands and multiple-use policies with respect to mineral rights leasing, exploration and development, environmental control, dedications for wilderness and recreation, and release of prior withdrawals, when warranted.
- Explore and develop offshore mineral resources.
- Correct any regulatory imbalances that impede U.S. domestic mining.
- Promote minerals R&D.
- Collect, analyze, and disseminate information concerning domestic and international long-range materials supply and demand.

Commerce and Technological Advance

- Assess materials needs cases relating to economic well-being and industrial production, and, in cooperation with the private sector, develop programs to meet those needs, including potential values and means for private sector stockpiling.
- Encourage conservation of and substitution for critical and strategic materials in key consuming industries.
- Promote the profitability of existing materials processing facilities that are strategically important.
- Encourage the development of advanced materials industries through federal R&D support, assistance in setting standards for new materials, facilitating limited R&D partnerships, and promoting R&D centers of excellence.

Performance

The performance of federal plans and programs in recent years in response to the requirements and responsibilities categorized above have been keenly scrutinized, in effect with "mixed reviews."

Chief Executive

On April 5, 1982, President Reagan submitted his National Materials and Minerals Program and Report to Congress as directed by the National Materials and Minerals Policy, Research and Development Act of 1980. The President's plan, among other matters, proposed policy initiatives for (1) defining the role of government in materials R&D, (2) reforming regulatory policies that discourage private materials R&D activities, (3) establishing through the Office of Science and Technology Policy (OSTP) some mechanisms for government-industry coordination of minerals and materials R&D, (4) establishing international information exchanges on materials R&D activities, (5) broadening the opportunities for U.S. private sector participation in the development and diversification of foreign sources of supply for strategic and critical materials through the International Trade and Development Program, and (6) providing intragovernmental coordination of federal materials and minerals R&D activities through the Federal Coordinating Council on Science, Engineering, and Technology (FCCSET) of OSTP. This slate of policy directives has been broadly acclaimed as the most comprehensive statement on materials policy since the Eisenhower administration.

Implementation of the President's plan, however, has also been broadly criticized for omissions in policy and policy direction. Among the problems cited are that (1) the principal focus is on minerals and mining, and balanced attention is not given to materials processing and use through finished products; (2) inadequate attention is given to strategies for resource recovery, conservation, and recycling and for waste materials disposal; (3) limited provisions are made for private sector participation and consultation in policy or program development; (4) the plan emphasizes domestic minerals development and inadequately addresses foreign investments and developments for establishing new sources of strategic materials supply; and (5) the establishment of the Cabinet Council on National Resources and Environment for coordinating overall policy guidance appears to sidestep the establishment of a permanent management entity within the Executive Office of the President for better focused assessments and for policy development and coordination. Administration officials have countered that the President's plan was intended as a starting point and that the 1980 act was general, contained many nonoperational phrases, and also failed the test of specificity.

Despite conflicting opinions concerning the merits of the 1980 act and of the 1982 President's plan, the two policy instruments taken together have focused the nation's attention on the seriousness of U.S. import dependency, the implications of a potential resource war with the Soviet Union, and the cumbersome organizational structure in government for taking prompt, coherent actions and for resolving materials policy conflicts.

Organizational paths for funding the most salient agencies responsible for key elements of the national materials program are diverse (R. C. Snyder, personal communication), as illustrated in Table 1.

Stockpile Management

As of September 3, 1983, the stockpile goals represented materials valued at $16.7 billion (Stockpile Report, 1984). However, materials actually in the stockpile on that date were valued at $11.1 billion, of which only $6.9 billion worth of materials could be charged against stockpile goals. The remaining $4.2 billion worth was excess. Of the

TABLE 1. National Materials Program Funding Paths

Agency	Division of Office of Management and Budget	Appropriations Subcommittee
Federal Emergency Management Agency (Natural Resources)	Transportation, Commerce, and Housing	Housing and Urban Development, independent agencies
General Services Administration (Stockpile)	Justice, Treasury, and General Management	Treasury, Postal, General Government
DOD	National Security	Defense
Department of the Interior	Natural Resources	Interior
Department of Commerce (not including National Bureau of Standards)	Transportation, Commerce, and Housing	Commerce, Justice, Judiciary, et al.
NSF, Department of Energy, National Bureau of Standards, other key federal technology offices	Energy and Science Division	Various

NOTE: The above tabulation is illustrative rather than all-inclusive. It does not include the various legislative authorization committees whose jurisdictions are also involved in funding.

61 groups of materials in the stockpile, only 24 groups equaled or were in excess of goals, and 37 groups were below goals. At the rate of purchase budgeting and congressional authorization ($120 million/year) from fiscal year 1983 to fiscal year 1985, nearly 82 years would be required to fill the $9.8 billion deficit. The first 35 years of that amount would theoretically be provided for from disposition of the $4.2 billion in excess inventory.

The seriousness of stockpile deficiencies (Stockpile Report, 1984) is readily apparent. Of the 61 family groups of materials and individual materials,

11 hold 0–19% of goal
6 are 20–39% of goal
11 are 40–59% of goal
3 are 60–79% of goal
6 are 80–99% of goal
A total of 37 are short of goal.

Only 24 of the 61 meet or exceed their 1980 goals.

Since enactment of the 1979 strategic stockpiling act, the annual materials plan (AMP) process (chaired by the Federal Emergency Management Agency [FEMA]) and the Stockpile Transactions Office (under the Federal Property Resources Service of the General Services Administration [GSA]) have implemented both acquisitions and surplus disposal activities. The latter have been of sufficient magnitude to cover the $313,739,614 cost of purchase obligations executed from fiscal year 1981 to 15 February 1984. Assuming that Congress authorizes the $120 million fiscal year 1985 budget request from the stockpile transaction fund, the AMP is estimated to enter fiscal year 1985 with a $130.6 million purchase authority (including $10.6 million available from the unobligated balance from the prior year).

Stockpile materials that have been purchased have presumably represented the higher priorities among the numerous commodities that have been short of goal. Table 2 shows purchases of the eight nonfuel minerals that have been acquired from fiscal year 1981 to February 15, 1984. Even for these priorities, at the annualized rate of their actual purchases, anywhere from 6.8 to 77.0 years will be required to meet their respective goals.

On March 13, 1981, President Reagan directed FEMA "to begin the first purchase program for the national defense stockpile of strategic and critical materials in over 20 years." He went on to say that "it is expected that larger purchases will be made as funds from sales of

TABLE 2. Nonfuel Minerals Purchases for the Stockpile (fiscal year 1981 to fiscal year 1984, as of February 15, 1984)

Material Purchased[a]	Quantity Purchased (cost)	March 1981 Shortage	March 1981 Inventory	Goal	Yrs to Meet Goal	U.S. Import Dependency
Bauxite metal (ldt)	3,300,000	12,141,119	8,858,881	21,000,000	10.8	96%[b]
(Jamaica)	($134,993,120)					
(Refractory)	($ 3,874,956)					
Beryllium (st)	30	171	229	400	11.4	W[c]
	($ 14,340,000)					
Cobalt (lb)	11,700,000	44,597,607	40,802,393	85,400,000	7.6	96%
	($113,750,000)					
Iridium (oz)	9,600	81,009	16,991	98,000	6.8	84%[d]
Tantalum (lb)	345,413	7,000,857	1,399,143	8,400,000	41.6	91%[b]
(minerals)	($ 11,391,607)					
Titanium (st)	4,500	173,535	21,465	195,000	77.2	10%
	($ 29,200,000)					
Vanadium (st) (pentoxide)	181	7,159	541	7,700	39.6	52%[b]

NOTE: During much of the period covered by this table, buyer's markets existed, owing to severe international commodities price depression, although administration budget requests and congressional authorizations were identical year by year, with the following exceptions of $100 million budgeted by the Carter administration for fiscal year 1981, and a reduction of the fiscal year 1982 budget from $120 million to $57.6 million in the course of concurrent budget resolution negotiations. The acquisitions of the various materials have varied from single purchases to three transactions during the 3.5 years. The table's projections of years required to achieve goals at these rates are merely arithmetic extrapolations. No better basis for forecasting progress is available, since the government has not published whatever more specifically defined schedules may have been formulated.

[a]Abbreviations: lb, pounds; ldt, long dry tons; oz, ounces; st, short ton.

[b]Applies to all grades of ores or metals.

[c]Withheld for proprietary reasons.

[d]For entire platinum group; iridium not separately published.

excess materials build up in the stockpile fund." Since the start of initial cobalt purchases of approximately $100 million in 1981, President Reagan has requested an additional cobalt purchase of $106 million, in fiscal year 1982.

In November 1981 the President directed FEMA to procure 1.6 million tons of Jamaican-type, metal-grade bauxite for the stockpile to coincide with his Caribbean initiative. Arrangements for a second Jamaican bauxite procurement for the stockpile were announced in June 1983. These bauxite procurements are being made through a combination of direct cash purchases and barter, using excess agricultural commodities through the Commodity Credit Corporation of the Department of Agriculture. These arrangements are the first use of agricultural barter to acquire raw materials for the stockpile in almost 15 years.

In December 1982 the administration announced that an exchange of excess stockpiled materials would be used in an upgrading program to add approximately 577,000 short tons of high-carbon ferromanganese and 519,000 short tons of high-carbon ferrochromium to the stockpile during a 10-year period. This program also has the additional objective of maintaining an emergency mobilization base for the domestic ferroalloy industry, but by itself it can do so for only a few years, at most.

Despite these initiatives, criticism has continued on the management of the stockpile, the financial alternatives to support the restructuring of the stockpile inventory, and the quality and suitability of some strategic materials in the stockpile for defense use. Completion of the cobalt quality study in September 1983 and of a priorities study in April 1984 have stilled this criticism in part, however.

The federal organizational structure for stockpile planning and management is unwieldy. Title II of the Omnibus Budget Reconciliation Act of 1981, amending the stockpiling act, requires the President to submit to Congress an AMP for the operation of the stockpile during the coming fiscal year and the succeeding 4 fiscal years. The AMP is developed each year through an interagency committee chaired by FEMA. Revisions of the plan are made jointly by the National Security Council, the Office of Management and Budget (OMB), and FEMA. Although FEMA is responsible for planning, programming, and reporting on the stockpile, responsibility for materials acquisition, storage, and disposition lies with GSA. The Department of Commerce is responsible for specifications for commodities to be acquired.

The primary funding sources for acquiring stockpile materials are provided by the Strategic and Critical Materials Stock Piling Revision Act of 1979. Section 9 of this act sets up the National Defense Stockpile Transaction Fund, and section 6 mandates that barter is to be encouraged in the acquisition of materials for the stockpile where it is practical and in the best interests of the United States. The stockpile transaction fund, a separate fund in the U.S. Treasury, receives all receipts from the sale of stockpiled materials. By law, funds deposited in the fund can be used only for the acquisition of needed strategic materials for the stockpile. In the Omnibus Budget Reconciliation Act of 1981, Congress stipulated that no disposal may be made from the stockpile after September 30, 1983, if the disposal would result in a balance in the stockpile transaction fund in excess of $500 million. Further amendments, intended to accelerate disposal of stockpile excess inventories and restrict the size of the stockpile transaction fund balance, are currently under legislative review in connection with the fiscal year 1985 Defense Authorization Act.

Problems have arisen because OMB prefers that the stockpile transaction fund be counted with other treasury funds in computing the balance of the federal budget. For this reason, OMB has consistently reduced requests for new stockpile purchases. As a result, the original 5-year AMP submitted to Congress as part of the fiscal year 1982 budget submission projected a transaction fund of $1.8 billion at the end of fiscal year 1987—nearly four times the $500 million congressional limitation. For this reason there have been pressures within Congress and from the private sector to take the transaction fund off budget. Furthermore, the Grace Commission* has recommended that budgeting of the transaction fund be transferred from GSA to FEMA in order to provide greater cohesiveness of planning. Conversely, if Congress were to remove 1981 disposal restrictions on excess silver in the stockpile (and assuming that it could be disposed of at market value), these budget-balancing pressures would be at least temporarily alleviated.

Barter can be an effective means both of acquiring strategic materials to meet stated goals and of reducing excess supplies of agricultural or other commodities. Principal authorities for the exchange of agricultural commodities for strategic materials are contained in the Commodity Credit Corporation Charter Act (as amended), the Agricultural Trade Development and Assistance Act (P.L. 480), the Stra-

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*A presidential commission established by President Reagan (under the chairmanship of W. R. Grace) to recommend cost savings in executive branch organizations.

tegic and Critical Materials Stock Piling Act, the Foreign Assistance Act of 1961, and the Federal Property and Administrative Services Act of 1949. However, an amendment to P.L. 480 restricts barter to bilateral arrangements.

Such arrangements restrict private sector participation and constrain the full exploitation of current international trading patterns and opportunities. House bill 3544, introduced by Congressman Charles Bennett, would allow barter transactions to use bilateral, multilateral, and open-ended contracts. Furthermore, it would remove requirements for market-value reimbursements to the agencies holding the surpluses, and it would provide for consultations and the use of services of private sector traders, brokers, and dealers. In view of the complexity of barter transactions, however, stronger interagency coordination from the Executive Office of the President is viewed as being necessary for this method of strategic materials acquisition to be an effective means of reducing stockpile shortages, but its value in acquiring high-priority stockpile materials may be limited.

Another issue concerns the physical condition, in quality and form, of the materials in the stockpile. Many of the materials in the stockpile have not been rotated since they were placed there in the late 1940s, and many changes in industrial technology have occurred since that time. FEMA and the Department of Commerce have conducted three in a series of studies to assess the quality of materials in the stockpile. In broadest summary, their results have found that some criticisms in earlier years were somewhat exaggerated. Moreover, these organizations have established a priority ranking of those materials that warrant corrective action.

One of these studies, conducted by the American Society for Metals (1983), assessed the quality of the cobalt inventory in the stockpile. It found that the 40.8 million pounds of cobalt purchased during the period 1947–1961 does not conform to the composition limitations necessary to meet current performance requirements, and this cobalt should be upgraded. However, the 5.1 million pounds purchased during 1981–1982 do meet the quality requirements of current technology.

In the case of titanium, the National Materials Advisory Board (National Research Council, 1983) found that the stockpile would be much more quickly responsive to a national emergency if as much as half of its total sponge authorization were replaced by ingots, and perhaps by alloy ingots and mill products. It can be expected that these and other such studies will call further attention to the obsolescence of a significant fraction of the current stockpile and to the need for a stronger, continuing technical advisory function for stockpile management. Whether or not the government has estimated the funding requirements for these upgrading requirements is not yet publicly known.

Foreign Policy

A number of administration foreign policy and related national security initiatives have critical bearing on the long-term security of strategic materials supplied to the United States. These include a navy program to build up its fleet to 600 ships, buildup of the merchant marine, the Caribbean initiative, initiatives by Assistant Secretary of State Crocker in southern Africa, the proclamation by President Reagan of the Exclusive Economic Zone (extending from a line 3 nautical miles off the coast of the United States and its island territories out to 200 nautical miles), and the pause called for by the President in signing the Law of the Sea Negotiating Text (in order to review the draft articles dealing with the seabed mining of multimetallic nodules).

The first initiative above relates to keeping vital choke points open on major sea routes used to transport petroleum and strategic minerals. The Grenada operation, for example, removed a major potential threat to important sea-lanes used for shipping petroleum and strategic minerals from South America, Africa, and the Caribbean islands.

The major policy thrusts being pursued by Chester H. Crocker, assistant secretary of state for African affairs, are aimed at improving political and economic stability and developing ties with all parts of southern Africa. These initiatives include encouraging private sector involvement in the region; seeking a withdrawal of South Africa from Namibia; seeking a withdrawal of Cuban troops from Angola; frustrating the subversive intentions of Libya; promoting progress in political power sharing in South Africa; maintaining intense open dialogue with Zaire, Zambia, and Zimbabwe; and promoting commercial interests in East and West Africa in cooperation with dominant European powers in these regions.

The recent announcement (Gwertzman, 1984) that the United States is sending a mission to Namibia to help monitor the disengagement of South African and Angolan forces from border areas may show progress toward a cease-fire and toward elections and independence for Namibia. The Namibian issue has been a principal barrier to improving trade and economic relations between the United States and principal African supplier nations of strategic materials.

The establishment of the Exclusive Economic Zone has added an additional 3.9 billion acres of offshore area for resource development to the existing 2.3 billion acres of onshore area in the United States and its territories. The discovery of massive polymetallic sulfide deposits at the southern Juan de Fuca Ridge, west of Oregon, opens up new prospects for future mining operations. These sulfide deposits are unusually rich in zinc and also contain cadmium and silver in economic quantities. Recent tests conducted by the Bureau of Mines (Sawyer, et al., 1983) show that these seafloor deposits can be processed to greater than 95 percent extraction by hydrometallurgical processing involving Cl_2-O_2* leaching. However, the mining of these deposits will have to be highly inventive, because the deposits are under 8,000 ft of seawater, and there are extensive communities of organisms and crustaceans that draw their nutrients from the hot geothermal plumes that spread the deposits.

Seabed manganese nodules are another potential source for increasing the world supply of nickel, cobalt, copper, and manganese. However, the Reagan administration looked upon the United Nations draft articles dealing with seabed mining in the draft Law of the Sea Treaty as being seriously flawed. Problems were found with limitations to national seaward jurisdiction, the rules of membership on the seabed mining authority, the formula for production control, the mechanisms for funding the authority, the establishment of a "common heritage" fund to redistribute proceeds to landlocked countries, technology transfer requirements, and undefined rights of American deep-seabed mining firms that would begin operations before the treaty would come into effect. Regardless of the future of this treaty, its mere existence will not by itself bring about exploitation of these valuable resources unless private investment can be attracted under the normal rules of risk management.

Domestic Mineral Development

One of the principal elements of the President's 1982 plan and report to Congress was the opening of appropriate public lands to mineral exploration. These elements focused on stepped-up efforts to take inventory of mineral resources on public lands and to facilitate access to mineral reserves on these lands. During its first year, the Reagan administration returned more than 3.2 million acres of public lands

*Entrained chlorine and oxygen gases in the leaching liquor.

from single to multiple uses. Several million additional acres have been reverted to multiple use since 1981. In addition, the Department of the Interior (DOI) has greatly increased coal leasing on federal lands and has revised a substantial fraction of regulations deemed harmful to the mining industry.

Since 1981 the U.S. Geologic Survey and the Bureau of Mines have been engaged in inventorying mineral resources on federal lands. Significant mineral investigations are being made on approximately 14 specific sites in Alaska to determine the occurrences and potential recoverability of chromium, platinum-group metals, tin, tantalum, columbium, and gallium.

The publication of the Minerals Data Source Directory by DOI in January 1983 has been widely acclaimed as a highly constructive initiative. However, the ability of the Bureau of Mines to acquire raw minerals data voluntarily from producers and processors depends critically on protecting the confidentiality of the data. A provision of the National Materials and Minerals Policy, Research and Development Act now provides for such confidentiality by forbidding general release of company data without the company's permission.

Secretary of the Interior William Clark announced on February 10, 1984, the establishment of a 25-member Strategic and Critical Advisory Committee to make recommendations to strengthen U.S. mining and to reduce dependence on foreign sources for such materials. The committee, to include representatives from industry, small business, and consumers, will report directly to the secretary, who also serves as chairman pro tem of the Cabinet Council on Natural Resources and Environment.

Commerce, Foreign Trade, and Investment

In response to the National Materials and Minerals Policy, Research and Development Act of 1980, the Department of Commerce has completed two case studies: "Critical Materials Requirements of the U.S. Aerospace Industry," issued in April 1982, and "Critical Materials Requirements of the U.S. Steel Industry," issued in March 1983. The former study identified no significant bottlenecks short of a major interruption of supply, and the latter study flagged manganese and chromium as being most serious to the disruption vulnerability of the steel industry.

In December 1982 the secretary of commerce established the Office of Strategic Resources (OSR), reporting to the assistant secretary for productivity, technology, and innovation, to coordinate all departmental activities related to strategic materials and resources. In April 1982 OSR announced a program to provide expertise in such fields as assessments of economic impacts on various industries, research on substitute materials, controls on exports, and developments in global negotiations on ocean floor mining. OSR has been influential in coordinating and cosponsoring FEMA studies on the quality of stored cobalt in the stockpile and on identifying the priority sequence for subsequent commodity-by-commodity quality studies. In November 1983 OSR was transferred to report directly to the under secretary for economic affairs.

In recent years foreign-based firms have penetrated a wide array of domestic markets, mainly because U.S. trade and investment policies are disordered, fragmented, and incomplete, owing to the lack of a coherent trade and investment strategy. The administration has proposed a sweeping reorganization to establish a department of international trade and investment to provide greater coherency in policy formation and implementation.

Two basic industries critical to our national defense mobilization base and seriously damaged by unfair foreign trade practices are the steel and ferroalloy industries. In 1982, imports took almost 22 percent of the U.S. steel market, compared with 9.9 percent in the 1960s and 15 percent in the 1970s. The year 1982 was the "year of the cases" for the steel industry, a year in which the Department of Commerce and the U.S. International Trade Commission handed down rulings on more than 90 antidumping and countervailing duty petitions, primarily against European Economic Community countries (American Iron and Steel Institute, 1983).

Most of these rulings confirmed that foreign steelmakers had materially injured U.S. companies by selling dumped and subsidized steel in the U.S. market. Evidence was found that advanced developing countries, such as Korea, Taiwan, Venezuela, Brazil, Mexico, and Argentina, were also engaging in exporting dumped or subsidized steel to the U.S. market. In the face of a serious world overcapacity for steelmaking, some of these countries, especially those with serious Third World foreign debt problems (Mexico, Brazil, and Argentina), have been targeting their steel industries with massive capital expenditures.

The plight of the U.S. ferroalloy industry follows similar patterns. Ferrosilicon, ferromanganese, and ferrochromium are vital ingredients in the production of steel. Since 1975, imports of ferromanganese have risen from 40 percent to 89 percent of domestic consumption. Similarly, imports of ferrochromium have risen from 46 percent to nearly 83 percent. The stockpile upgrading program for ferrochromium and ferromanganese is considered by industry leaders to be too modest to preserve significant furnace capacity for these commodities.

The Soviet Union has recently attempted to cripple the domestic production of ferrosilicon, which is the last bastion of the U.S. ferroalloy industry (65 percent of demand is produced domestically) (Auerbach, 1983). When the U.S. steel industry was suffering a prolonged recession in 1983, the Soviet Union shipped 5,365 tons of 50 percent ferrosilicon to the Port of New Orleans with a declared value of one-third of the domestic price. This shipment was the first of a planned U.S. market penetration by the Soviet Union of 50,000 tons of ferrosilicon over a 2.5-year period.

To counter such unfair trade practices, the ferroalloy industry has asked the Department of Commerce to set a "breakpoint" duty for imports of all ferroalloys. This duty would be based on the cost of producing a ferroalloy in an efficient American plant and would include a reasonable profit for the company.

U.S. policymakers have expressed considerable concern about the decline of mining investment in developing countries over the past decade. This concern was expressed by Congress in the National Materials and Minerals Policy, Research and Development Act of 1980. Section 4(9) of the act requires the President to increase the reliability of overseas supply sources by assessing the opportunities to promote cooperative multilateral and bilateral agreements for materials development in foreign lands.

In response to the act, the administration has shown a preference for private over public investments for Third World assistance. Accordingly, efforts have been made to increase private sector investment programs within the Agency for International Development (AID), to expand the International Development Corporation Agency's Trade and Development Program, and to form a model bilateral investment treaty to provide a common frame of reference and legal base for such investments.

A 1982 study (General Accounting Office, 1982) of federal programs for encouraging mining investment in developing countries criticized the administration's policies for not acknowledging existing overseas investment initiatives. Such initiatives include those undertaken by U.S.-supported multilateral development bank agreements and by the minerals and energy program of the Overseas Private Investment Corporation. The study also concluded that the lack of a coherent investment strategy with well-defined materials needs was a major impediment to obtaining the highest-priority materials through foreign investment programs.

Investment programs promoting mining investment have been only marginally helpful since 1978, according to GAO. This is due generally to depressed minerals markets that have affected the economic viability of proposed or potential projects. Furthermore, the lack of support, failure to implement, and funding limitations of insurance plans that mitigate political risks of private investments in developing countries were cited as major stumbling blocks in developing new foreign mining operations for strategic minerals.

Research and Development

In his April 5, 1984, National Materials and Minerals Program Plan and Report to Congress, the President focused attention on the federal government's role to concentrate R&D efforts in minerals and materials. The President specifically tasked OSTP to direct effective mechanisms for constructive R&D program coordination among the applicable agencies in implementing the national minerals and materials policy. The President also reaffirmed the Committee on Materials (COMAT), under FCCSET, for the purpose of coordinating federal minerals and materials R&D. COMAT (actually, COMAT IV) set as its first order of business an inventory of federal minerals and materials R&D for analysis, assessment, and planning purposes. Although an inventory for fiscal year 1982 was issued in March 1983 (Office of Science and Technology Policy, 1983), a comprehensive analysis of the data has not yet been released. In addition to the inventory, COMAT has organized coordinated task forces concerned with rapid-solidification technology, materials sciences (academia), defense materials availability, essential (including critical and strategic) materials, and welding technology.

The administration's policies on R&D were summarized in "Special Analysis K" of the fiscal year 1983 budget and were expanded upon in the Annual Science and Technology Report sent to Congress in April 1982. The policy states in part that "the Government should focus its direct R&D support on those areas where there is substantial prospect for significant economic gain to the Nation, but where the private sector is unlikely to invest adequately in the national interest because the benefits, in large measure, are not immediately 'appropriable' by individual firms."

This policy has had a significant impact on restructuring federal R&D budgets for fiscal years 1982–1984. Over fiscal years 1981–1983 the NSF budget for materials science increased 6.2 percent, compared with a 16.5-percent increase for the overall program in mathematical and physical sciences. However, special emphasis for increased funding in this program was given to microelectronics, robotics, integrated optics, and special-purpose computer architectures. Funding levels for materials R&D between fiscal years 1980 and 1983 in the other federal departments and agencies have remained relatively unchanged, despite the general de-emphasis of federal support for applied and development research and the sharp reductions in fossil fuel, solar energy, energy conservation, and other nonnuclear energy R&D programs in the Department of Energy (DOE).

Significant budget erosion for materials R&D has occurred over this period in DOI (Bureau of Mines) and the Department of Commerce (National Bureau of Standards [NBS]). Examples of program casualties that are directly related to the materials cycle for critical and structural materials are programs at NBS in recycled materials (secondary materials) and the Minerals Institute Program administered by the Bureau of Mines, under which 31 colleges and universities from across the nation have received research and training support in minerals engineering. These programs were targeted for elimination on the basis that they represented R&D work done for specific industries and, therefore, should have been transferred to the private sector.

Although targeted for zero funding in the DOI fiscal year 1983 budget submission, the Minerals Institute Program is funded through fiscal years 1983 and 1984. In addition to the 31 mineral institutes, generic mineral technology centers were established in fiscal year 1982 to receive research grants. The generic areas include mine system design and ground control (Virginia Polytechnic Institute and State University), comminution (University of Utah), mineral industry waste treatment and recovery (University of Nevada), pyrometallurgy (University of Missouri—Rolla), and respirable dust (Pennsylvania State University and West Virginia University).

Strategic Materials R&D

Significant R&D programs to reduce U.S. dependence on critical and strategic materials have been established in the Departments of

Energy, Defense, Interior, Commerce, and Transportation and in NSF and the National Aeronautics and Space Administration (NASA). Most of these programs focus on conservation, recycling, substitution, and life extension strategies, whereas the Bureau of Mines program additionally focuses on devising new extractive metallurgical concepts for treating domestic low-grade and complex resources. Although the Bureau of Mines budget continues to decline, the bureau's strategic and critical materials resource activities continue to be given high priority.

NASA has also played a role by tackling the aerospace industry's needs to minimize the use of strategic materials for advanced aerospace systems. NASA's Conservation of Strategic Aerospace Materials Program, which is already phasing out, has been focused on strategic element substitutions (principally cobalt) in stainless steels and nickel-base alloys, on materials processing, and on new classes of high-temperature metallic materials.

Industry has also discovered that there are clear and immediate actions driven by economic, defensive, and opportunistic incentives to reduce its dependency on some strategic materials. Many of these incentives do not await government action or policy intervention. Some of the approaches being pursued are outlined below.

- Extraction and processing—Much of the materials extraction and processing R&D conducted by the Departments of Agriculture, Commerce, and Interior was mandated under section 8 of the Strategic and Critical Materials Stock Piling Act of 1979. Bureau of Mines projects include the development of new high-temperature alloys that would permit the substitution for all or part of chromium commonly used in such alloys, chromium-free and bauxite-free refractories for steelmaking, new sources of cobalt and nickel through the processing of laterite ores near the Oregon-California border and from the recovery of cobalt and nickel from Missouri lead ores, and processes for extracting tungsten from California Searles Lake brines. Extensive work has also been done by the Departments of Agriculture and Commerce to establish the economic feasibility of developing the guayule plant as a domestic source of natural rubber.
- Substitution and displacement—R&D efforts are exploring the use of advanced and alternative materials that will substitute for or displace the overall need for strategic materials. Among the classes of materials being explored for this role are composite materials (e.g., metals, polymers, or glasses reinforced with graphite, glass, ceramic,

and polyamide fibers); rapidly solidified metals; structural ceramics (especially those "toughened" by internal discontinuities); intermetallic compounds (and alloys strengthened by intermetallic compounds); structural polymers; coated graphite and woven graphite composites and laminates; and advanced coatings, ion implants, laminates, claddings, graded layers, and dual-composition concepts that reduce the total requirements for critical materials.

Many of these advanced materials can displace strategic materials where high-temperature strength, erosion resistance, corrosion resistance, and low maintenance costs are key design parameters. Following are some specific examples of substitutions for chromium-bearing alloys:

— The Bureau of Mines is exploring a series of iron-base alloys that use molybdenum, titanium, aluminum, and silicon additions instead of chromium for applications requiring high-temperature, oxidation-resistant performance (Department of the Interior, 1981). Candidate iron-base alloys containing various combinations of aluminum, molybdenum, tungsten, columbium, nickel, and silicon are being actively explored by others. One such alloy, containing manganese, silicon, and copper, is being developed as a replacement for chromium-bearing spring steels (Department of Commerce, 1981).

— Rapid-solidification technology looks particularly promising for improving surface hardness and corrosion resistance through compositional homogenization and microstructural refinement. An iron-aluminum alloy containing a finely dispersed titanium diboride phase has already been commercially introduced for producing wire-drawing dies. DOD is actively pursuing a variety of rapid-solidification technologies to develop new families of alloys that will permit less use of chromium, cobalt, and other critical and strategic materials.

— Near-net-shape technologies are already providing dramatic improvements in chromium conservation through reduced scrap generation and recycling. Dramatic savings in chromium use are already being realized in the use of hot-die, superplastic forgings to reduce grinding and machining losses in the manufacture of superalloy jet engine disks and in the increasing use of powder metallurgy in the manufacture of high-alloy bearings, tools, and dies.

— Advanced surface modification technologies are also displacing chromium in both coating and base alloy compositions. These new surface modification processes not only reduce the strategic metal content in the coatings applied but also greatly extend the life of the tool or part. For example, significant cost savings have been projected for the use of TiN*-coated drills.

— The automotive industry is replacing chromium used in exterior trim, wheel covers, seat belts, windshield wipers, suspension springs, iron castings, engine components, gears, bearings, and other parts through selective material substitutions. There is the potential of reducing 3 of the 5 lb of chromium used in the average 1980 U.S. car (Department of Commerce, 1981). Moreover, with the development of stratified-charge diesel engines, the approximately 2 lb of chromium currently used per car for catalytic converters could be eliminated.

Examples also abound for substitution technologies for other strategic materials. For example:

— Ceramic-ferrite magnetic materials are displacing cobalt-rich alnico† alloys, and neodymium-iron-boron materials have great potential for displacing samarium-cobalt materials for magnet applications requiring high-energy products.

— The use of lead-free gasolines has made possible the use of cobalt-free alloy systems for the hard facing coatings of engine exhaust valves.

— Base-metal thick films have been developed to replace platinum-group metals in hybrid circuits. Also, advanced coating techniques are minimizing the use of noble metals in connector contacts.

— The increasing use of ladle refining in steelmaking makes possible very low levels of sulfur content (parts-per-million levels are possible) and the reduced use of manganese to "tie up" sulfur.

Many of the above substitution programs for cobalt were prompted by the supply disruption resulting from the invasion of Zaire's Shaba

*An intermetallic compound of titanium and nitrogen.

†Alloy of aluminum, nickel, and cobalt.

province by Katangan dissidents, a disruption that caused the official price of cobalt to increase from about $7 per pound in May 1978 to $25 per pound by February 1979 (spot prices rose as high as $40–$50 per pound) (Congressional Research Service, 1982). Industry, motivated as much by concern over future supply and price uncertainty as by market price per se (the spot market price for cobalt was $4 per pound before the end of 1982), has continued to invest in substitution technologies for cobalt.

- Conservation through design and processing—Strategies employed by industry to conserve the use of strategic materials include: greater use of computer-aided product design and manufacturing to control the excessive use of strategic materials; and greater use of manufacturing techniques that produce parts to near-net shape, thereby reducing metal removal operations and scrap generation . . . for example, investment and precision die-casting, powder metallurgy, precision-stepped extrusions and forgings, improved welding and joining techniques, superplastic forming, isothermal and near-isothermal forging, and hot-isostatic (and in some cases cold-isostatic) pressing.
- Reclamation—Several means can be and are being employed to reclaim and recycle high-value strategic materials from scrap and wastes. These include assessing current technology and devising procedures for rapid identification and sorting of scrap metals; reclaiming mechanically cleanable materials, such as shop floor scrap, grinding swarf, and chemical machining sludges; identifying and tracking scrap through all stages of manufacture and collection to maintain pedigree; and developing advanced extractive technologies to minimize the buildup of deleterious trace elements in recycled scrap and to produce master melt alloys from contaminated wastes.

As an example of government-funded reclamation efforts, the Bureau of Mines has developed processing technologies for recovering chromium from slags, furnace dusts, and other particulate wastes; for reducing chromium losses in electroplating operations through the recycling of waste chromic acid solutions; and for reducing the chromite additions to refractories by improving the magnesia grains used in these refractories (Department of the Interior, 1981).

The development of a science and technology program for secondary materials—that is, the extraction of strategic and critical materials from urban, industrial, and mining wastes—can have important returns. Secondary materials represent a major shortcut through the materials cycle. The processing of secondary materials not only requires substantially less energy use than the processing of primary materials but also results in less net waste to dispose of and fewer problems in environmental management. Since fewer man-hours of labor are usually required to produce a ton of recycled metal versus the time required for primary production of a ton of metal from ores, substantial productivity gains can also be realized. Moreover, a ton of secondary materials processing capacity, as in the case of a ton of domestic primary production capacity, can displace 3 tons of material from the strategic stockpile, based on a 3-year stockpile objective.

- Life extension—The demand for products having longer life, greater reliability, and higher quality has become a growing societal expectation over the past decade, extending from consumer products to sophisticated military systems. Because of this trend, the annual per capita consumption of materials in general and strategic materials in particular should gradually decline throughout the remainder of the century and beyond. Some of the enabling technologies that contribute to life extension strategies are computer-aided design, manufacture, and inspection techniques that improve structural integrity, reliability, and resistance to failure; improved coatings, alloys, and microstructures (e.g., through rapid-solidification metallurgy) that minimize wear, erosion, and corrosion; and improved nondestructive evaluation, analysis, repair, maintenance, in-service monitoring, and rework procedures that extend the lives of existing structures and components that contain strategic materials.

From the foregoing it is evident that industry can take numerous actions to reduce U.S. dependency on strategic minerals. There are undoubtedly also numerous opportunities to substitute for the use of these materials in chemicals, catalysts, and other essential industrial uses not addressed here. In the event of a national emergency, the nondefense applications of these materials will be the ones most seriously affected.

Advanced Materials R&D

The federal laboratories have been redirecting their programs to address the nation's vital need for advanced materials. The burden has fallen heaviest on DOE, which has the largest amount of funding for materials R&D (approximately 26 percent of the total for fiscal year 1983) (Office of Science and Technology Policy, 1983). DOE laboratories also operate unique, large facilities that support basic materials research, and DOE makes these facilities available to university, industry, and government researchers in materials science.

The efforts of the Lawrence Berkeley Laboratory to establish a national center for advanced materials is the most visible of recent initiatives. However, the establishment of the Center for Materials Science at Los Alamos National Laboratory, the High-Temperature Materials Laboratory at Oak Ridge National Laboratory, a new materials development laboratory at Lawrence Livermore Laboratory, and a more focused Division of Materials Science and Technology at Argonne National Laboratory are other noteworthy examples. All of these laboratories are attempting to increase private sector participation through advisory committees, joint basic research, technology transfer initiatives, and greater access to major facilities for proprietary research.

A major administration policy has been to stimulate private sector R&D investment. The principal mechanisms for implementing this policy have been R&D tax credits, accelerated depreciation schedules for R&D equipment, models for R&D limited partnerships, and antitrust and intellectual property reforms proposed in the administration's pending National Productivity and Innovation Act of 1983.

R&D spending for primary metals industries was already on the increase before the establishment of these incentives, from $613 million to $693 million from 1979 to 1983 (Shapley et al., 1982). However, the impacts of the recession and any continued erosion of these industries by foreign competition can be expected to have greater influences on their future levels of R&D expenditures than would federal R&D incentives.

Both federal and state programs have been established to stimulate university-industry partnerships in R&D programs related to high-technology enterprises and productivity-enhancing technologies. NSF has established university-industry research centers in polymers (University of Massachusetts and Case Western Reserve University), welding research (Ohio State University), interactive computer graphics (Rensselaer Polytechnic Institute), communications and signal processing (North Carolina State University), ceramics (Rutgers University), and building energy utilization (Iowa State University) (Eveland and Hetzner, 1982). These centers are considered by NSF to be experimental institutional models for promoting collaborative research between industry and academia under consortium funding arrangements.

Similar model programs, to include research institutes, research parks, and special program linkages between universities and entrepreneurs, are being tested in several states. Most of these programs are focused on microelectronics, biotechnology, computers, communications, robotics, and similar high-technology fields. However, some programs—notably, those in Michigan, North Carolina, Ohio, and Pennsylvania—are also giving specific emphasis to materials processing, advanced polymers, high-technology ceramics, and electronic materials.

The Reagan administration has generally de-emphasized international R&D initiatives. Sharp cutbacks in international programs in the first Reagan (fiscal year 1982) budget for NSF signaled contraction of the NSF role to "core" basic research programs. Export licensing requirements imposed on universities doing research on militarily critical technologies have also curtailed international research collaborations and information exchanges in these and related fields. However, the administration has promoted the establishment of U.S. Geologic Survey missions abroad to assist developing countries in the exploration and inventory of minerals. It has also encouraged private sector technology assistance through AID and has established a precedent for providing assistance through AID for science and technology infrastructure development in developing countries under the U.S.-Thailand Science and Technology Corporation Agreement, signed in April 1984.

CONCLUSIONS

From this review of the status of materials science and technology, and of the related policy implications, the following can be concluded:

- Major improvements in government organization and management structure are distinctly required if national security, economic health, and international relations are all to benefit from significant advances in key technologies.
- The unwieldy organizational structure of the federal government makes coordinated planning and concerted action difficult in such vital areas as stockpile management, the exploration and development of domestic resources, and the transfer of government-funded technology to industry. Improved methods for the critical assessment and coordination of federal programs across the federal departments and agencies are needed.
- The stockpile is still seriously inadequate for serving its intended

purposes. The current planning and budgeting structure contains too many barriers and conflicting interests. An off-budget transaction fund and streamlined management authority are needed to upgrade the quality and utility of the stockpile for national preparedness.

- The involvement of industry in policy advisory and review roles has been ad hoc and has not been sustained. Since industry is the major ultimate supplier and user of strategic materials and will control the rate of introduction of substitutes for strategic materials, a more meaningful and enduring relationship should be defined.
- Existing R&D policies have not given adequate priority to developing advanced techniques for the exploration of domestic mineral resources or for improving extraction techniques for marginal reserves, yet major discoveries of new domestic sources of supply have been made in the past 15 years with much less than state-of-the-art exploration techniques.
- Developing countries, and especially those with valuable energy and mineral resources, will increasingly look to materials technologies to increase the quality of life of their people. These countries are primarily interested in technological know-how and capital investments in existing materials processing and manufacturing technologies, which in the United States reside in the private sector. Future international development programs for developing countries should focus on improving the technological infrastructures of these countries to improve their capabilities of acquiring and using those technologies transferred under normal business arrangements with U.S. industry and commerce.

As a final note, materials R&D in the United States is currently in a healthy state. The number of world-class centers for basic research in advanced materials is on the rise. Likewise, industrial support for academic research overall has more than doubled in constant dollars since 1970. Total industry funding for R&D now surpasses that of the federal government, reflecting a better balance between technology application and new technology generation. However, stepped-up investments in advanced materials technologies by the Soviet Union, Japan, Canada, and Europe indicate that the U.S. share of the world's technology base in materials will continue to decline. Therefore, the risk of being "blindsided" and surprised by materials developments occurring elsewhere in the world will increase in the future. A posture of technological openness rather than technological arrogance will serve our nation best in the future.

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The Energy Sector

Edward A. Frieman

STATUS

THE ENERGY PROBLEM facing us was only dimly perceived a decade and a half ago. The oil embargo of 1973, natural gas shortages in the winter of 1976–1977, gasoline lines in 1979, and the contribution of energy to inflation and recession led to public confusion, political debate, and the introduction of policies that have turned out to be questionable. More recently, decreasing oil prices, supply gluts, and a shakier Organization of Petroleum Exporting Countries (OPEC) structure, combined with the effects of the worldwide recession, have led to statements that energy is no longer a national problem. Once again the issue is clouded, and a clear national focus is lacking.

Our task in this symposium, the exploration of correlations between technological frontier activities and foreign relations concerns, is compounded in the case of the energy sector by the multidimensional nature of the problem. Energy is recognized as a significant component of economic development, of the social fabric of nations, of the political and geopolitical process, and of national security concerns. A central issue in the eyes of many serious analysts today is the belief that near-term market signals are masking the inherent, underlying, real structural concerns. It is appropriate, then, in considering the energy sector to keep these broader issues in perspective so that we also do not mask some of the more crucial aspects of the problem.

Three recent comprehensive studies, in addition to many other detailed technical reports and analyses, have examined a number of aspects of the longer-range energy problem. *Energy in Transition, 1985–2010* from the National Research Council of the U.S. National Academy of Sciences, dealt mainly with the U.S. posture in that time period from the point of view of 1979. *World Energy Outlook*, published in 1982 by the International Energy Agency (IEA) of the Organization for Economic Cooperation and Development (OECD), treated the problem through the year 2000, with a major focus on the IEA member countries. *Energy in a Finite World*, from the International Institute for Applied Systems Analysis (IIASA), concerned itself with the global picture through 2030. Although these three publications do not agree in detail, they share a wide area of commonality about the general trends that are essentially dictated by some of the more inexorable aspects of supply and demand, and about the technologies available to cope with these demands.

It is convenient in thinking about the problem to distinguish four time phases. The first is tomorrow. This time phase is characterized by issues that are being debated now in the political domain—natural gas deregulation, the future of the breeder reactor and the nuclear industry, nonproliferation policies, coal leasing on federal lands, the disposition of the Synthetic Fuels Corporation, structural issues of utility financing, purchases for the strategic petroleum reserve, and what to do about acid rain. The second phase, covering the next 2–3 decades, will most likely be dominated by the oil supply problem and the attempts of nations to bring their reliance on imported oil down to more acceptable levels. The third phase, perhaps a 4–5-decade time span beyond 2010, will tend to be characterized by a worldwide transition away from conventional oil as a dominant primary energy source. The technology and resources necessary to accomplish that transition are under intensive study now. The last phase, toward the end of the next century, should see the beginnings of the final transition to a sustainable, long-term global energy system that is only vaguely apparent to us now. However, short of new scientific breakthroughs, the basic technologies that must be developed are now known.

Clearly, technology plays a central but different role in each of the longer-range time domains. One of the issues before us is which of the plethora of potential technologies will be developed. The resolution of this question necessitates a broad-gauge research and development (R&D) program to allow sufficient knowledge to be accumulated about the many factors surrounding the proposed technologies, including their economic, environmental, and public health and safety impacts. (R&D expenditures, however, are decreasing.) It also necessitates a clearer enunciation of longer-range energy policies in both the domestic and the foreign arenas in order to provide a more stable framework for strategic planning in energy-related matters in both the public and the private sectors.

In sharp contrast to some of the other technological sectors considered in this symposium, such as biotechnology, microelectronics, and new materials, energy technology cannot easily be characterized in terms of important innovations in the last 10 years. On the contrary, there is a vast inertia in the global energy system. Many of the key technologies upon which the energy system rests, such as oil refineries and electricity-generating plants, have lifetimes on the order of 25–30 years; hydroelectric projects and buildings may have lifetimes on the order of 50 years or longer. Therefore, two lifetimes, or approximately 50 years, may be required before major technological transformation takes place. Moreover, market penetration proceeds with glacial speed. Historically, for a new energy source to increase its share of the market from a few percent to a significant fraction of the primary energy market typically takes 50 years.

The one critical area where a number of the foregoing remarks do not necessarily apply is in the arena of energy efficiency and conservation. There, technology and innovation are rapidly advancing. Retrofits to existing stock are being made, more fuel-efficient cars are in production, electric household appliance efficiencies have improved, and heat pumps in large numbers are being utilized. Conservation has become publicly acceptable, and total U.S. energy demand is down, partially attributable to these efforts.

Many of the energy studies carried out in the past rely on computer-based complex modeling procedures that attempt to encompass a large number of aspects of the real world, including issues of market penetration, energy/gross national product (GNP) ratios, population growth, resource limitations, future energy price trajectories, and technology characterization. It hardly needs emphasizing that such projections only have value as a way to organize one's thoughts on a particularly dense and tightly coupled dynamic system. Further, by exercising these models under a variety of differing parametric assumptions corresponding to a range of worldviews, indications of changing trends in the behavior of the global system can be sought. We will examine some of these projections below.

Rather than discuss specific supply and demand scenarios at this point, I will first make some crude estimates to bound the problem, as done in the IIASA report. The worldwide average per capita power consumption today is on the order of 2 kilowatts (kW). (A typical U.S. city of 50,000 requires 100,000 kW for its residential needs alone.) The world of 2030, according to some projections, will have a population of 8 billion people. This yields a requirement for 225 million barrels of oil per day equivalent, or 16,000 one thousand-megawatt (MW) electric plants. Present consumption is severely maldistributed, with much of the world's population utilizing only 0.2 kW per capita. With increasing economic development, the per capita average could grow to 3, 4, or even 5 kW. For those used to thinking in terms of quads (10^{15} British thermal units [Btu]), this calls for 480 to 1,200 quads of energy supply. In comparison, U.S. consumption in 1982 was about 73 quads, and the U.S. Department of Energy (DOE) 1983 National Energy Policy Plan (NEPP) midrange projection for the year 2000 envisions 93 quads. Estimated capital investments to produce the 2030 supply run from $30 to $50 trillion in today's dollars and average about 4 percent of the gross world domestic product.

Some breathe a sigh of relief when they recognize that the planet can, in principle, provide these staggering energy demands; others are horrified at the imagined despoliation that might result. The long-range concerns are that even this level of demand cannot be indefinitely sustained, nor is it yet clear how we will manage to reach even this state.

RESOURCES AND TECHNOLOGIES

It has long been recognized that a mix of resources, as well as technologies to exploit these resources, is needed to fashion deployment strategy for supply and demand balance. In the following section we briefly survey the current estimates of reserves of primary energy and of the more highly speculative resource bases, as well as the energy technologies necessary to convert primary energy to various secondary energy forms.

Oil

Worldwide oil reserves are estimated at 6.7×10^{11} barrels, whereas global conventional oil resources are estimated at 2.3×10^{12} barrels. Proven reserves for the United States are on the order of 2.7×10^{10} barrels.

The oil industry supports its own technology development in exploration and production in a largely proprietary mode. Major thrusts will be toward offshore production, deeper drilling where necessary, and exploiting resources under increasingly harsh conditions. Research on catalysis will continue in efforts to improve the efficiency of conversion of oil to gasoline, jet fuels, diesel oil, naphtha, and the like.

At present, two-thirds of the oil in known fields remains unrecovered. Primary production techniques rely on natural reservoir drive mechanisms. Secondary recovery, using water flooding, is commonly used when the natural driving forces wane. Primary recovery and secondary recovery taken together typically leave two-thirds of the oil in the ground. Technology for enhanced, or tertiary, recovery is under development and in field testing now. Chemical flooding, gas flooding, and thermal recovery using steam flooding are the techniques under investigation. Much of this work has essentially come to a halt in the present climate.

As conventional oil resources continue to diminish, a natural turn toward "unconventional" oil, namely, heavy oils, tar sands, and oil shale, is expected. The technology for exploiting these unconventional oil resources is still in its infancy, necessitating a future major research, development, and demonstration program. The worldwide resource base is estimated to be another 2.3×10^{12} barrels. U.S. shale resources alone are estimated to be approximately 3,700 quads, or 6.3×10^{11} barrels. Land use, water, and other environmental concerns could limit the utilization of this resource.

Although there is mild controversy regarding this point, most serious students of the subject predict a continuing worldwide downward trend in finding rates for the less expensive and higher-quality oils.

Natural Gas

Natural gas is one of the most attractive resources, since its primary and secondary energy forms are identical. It is clean, easy to distribute, and easy to use. Worldwide resources of natural gas are assessed to be 280×10^{12} cubic meters, or 10^4 quads. There do not appear to be significant R&D issues associated with this technology. Major future interest will eventually focus on unconventional gas resources that include, for example, Devonian shales, tight gas sands, methane from coal beds, and gas hydrates. Although their composition is conventional, these resources are generally locked in rock and require fracturing to release economic quantities of gas. The magnitude of this resource is not well-established, with estimates ranging from 1 to 10 times the conventional resource. Another potentially large source of unconventional gas is contained in the so-called geopressured resources, which are hot fluids that are under high pressures and contain dissolved and trapped methane. These resources have the potential for recovery of methane, thermal energy, and mechanical energy. In the current climate, R&D in this area is on the wane.

Coal

World coal resources are estimated to be 300,000 quads, whereas reserves of approximately 1,800 quads at economic prices are thought to be easily achievable. At somewhat higher costs the reserves expand to 6,000 to 9,000 quads. Domestic reserves are estimated at 6,000 quads out of a total U.S. resource of 80,000 quads. Limitations and constraints are myriad if attempts to achieve high levels of coal use are made. The opportunities for technology are quite significant throughout the whole coal cycle, from mining to end use.

Mining Technology

Underground mining is currently based on longwall and room-and-pillar techniques. It is thought that modern robotic and other technologies could improve mine safety and productivity in a major way. Surface mining is based on four techniques: area, open-pit, contour, and auger mining. Problems of erosion, water pollution, land use, and reclamation often ensue. No significant new technology has yet emerged in these areas.

Advanced Technologies for Coal Combustion

To improve efficiency, lower costs, and reduce environmental impacts, a number of new approaches to coal combustion are under development. Although, in general, these are not ready for wide commercial introduction, enough promise is shown for continuing R&D support.

Fluidized-bed combustion, in atmospheric and pressurized forms, entails burning coal in a mixture with limestone, which absorbs sulfur, with the whole suspended in a turbulent stream. It is hoped that these methods can replace scrubbers for meeting sulfur oxide emission standards. The pressurized version is less well developed but holds greater promise for higher efficiency and lower sulfur oxide and nitrogen oxide emissions. If acid rain control requirements are phased in in the future, these technologies could play a greater role.

Combined-cycle generation also shows a good deal of promise for high efficiency and cleanliness. The basic notion is to use the exhaust heat of a gas turbine's first stage as a source of steam for a steam turbine's second stage. This is inherently one of the most efficient power cycles available. At present there is a significant installed capacity, fueled by natural gas or petroleum distillates. In its use as a coal combustor, a pressurized, fluidized-bed–generated hot gas could be utilized as a first-stage fuel. Another approach involves a coal gasification unit producing medium-Btu gas as a first stage. Coal-to-electricity efficiencies of 45 percent are likely for such systems. Control of sulfur oxide, nitrogen oxide, and particulates in such configurations is thought to be far more cost-effective than are current scrubbing techniques used in conventional power plants.

Fuel cells convert energy to electricity through electrochemical rather than thermal means. They are potentially highly efficient and nonpolluting and are capable of modular installation. Their efficiency does not vary appreciably over a wide range of load demands, making them ideal in a load-following mode. Their desirable attributes make them a likely way to provide a major source of energy from coal in the future.

Magnetohydrodynamic generation is another technique in which electricity can be produced from coal without the need for a turbine by using the electrically conducting properties of hot gases. As a commercial technology it is still many years in the future.

Cogeneration of electricity and heat is a potentially attractive way of conserving fuel in small and medium-sized coal-fired units. This technology could be developed as a replacement for oil and gas in decentralized integrated systems for airports, office complexes, and so forth, if small combustor development can be carried out.

Synthetic gas from coal is an old technology that was dropped as natural gas became available through long-distance pipelines. Such processes as Lurgi, Winkler, and Koppers-Totzek use a gasifier in which the coal is heated with oxygen and reacted with steam, producing low-Btu and medium-Btu gas. When high-Btu gas equivalent to the heating value of natural gas is desired, a further methanation step is required. R&D on improving these processes is under way at relatively low levels.

Coal liquefaction, or the production of synthetic liquid fuels, has long been theoretically understood. Coal is a hydrocarbon in which the hydrogen-to-carbon ratio is low. Oil is a hydrocarbon in which the ratio is higher. Thus, the general aim of all synthetic liquid fuel production techniques is the addition of hydrogen by various means. The approaches to the problem fall into four different categories: indirect liquefaction, pyrolysis, solvent extraction, and catalytic liquefaction.

Indirect liquefaction is in commercial use in the SASOL plants in South Africa. In this process, the coal is first gasified, then cleaned, and finally converted over a catalyst to a range of final liquid products. Indirect liquefaction has a low thermal efficiency and will therefore probably not be pursued on a commercial scale in the United States.

The pyrolysis process involves heating coal in the absence of oxygen, with hydrogenation accomplished by using hydrogen from the coal itself or by using a stream of hydrogen gas. This process will most likely not be a candidate for future development, since the product slate is of poor quality.

Solvent extraction techniques depend on pulverized coal mixed with a hydrogenated solvent to get the additional hydrogen needed. Separation of the unused coal and ash from the final liquid product has proved to be a difficult technical problem. Catalytic liquefaction can, in principle, avoid this problem by suspending the coal in heavy oil as it passes over a catalytic bed. The heavy oil then serves as an additional hydrogen donor.

Midscale demonstrations of all of the foregoing technologies were under way in the United States but have now largely been stopped.

In sum, coal remains a most valuable resource that is surrounded by a host of constraints on its future development. A number of promising technical approaches are in the offing, but such issues as acid rain and carbon dioxide worldwide buildup require resolution.

Nuclear Energy

Nuclear power is, of course, generated by the liberation of heat when fission of heavy elements takes place in a nuclear reactor. Nuclear fuel consists of isotopes that are easily fissioned by slow neutrons. Of these fissile isotopes, uranium 235 is the most abundant in nature. Fertile isotopes, such as uranium 238 and thorium 232, are sources for other fissile isotopes, plutonium 239 and uranium 233. In the light-water reactors (LWRs) used commonly in the United States, the raw material of reactor fuel is uranium.

Uranium resources on a worldwide basis are estimated to be 24.5 million tons. Thorium resources, which could be used in other fuel cycles, are estimated at 1.2 million tons. Both of these estimates are speculative.

Nuclear technology is used in three stages of the nuclear fuel cycle: front-end activities, reactor operation, and back-end activities. The front end of the cycle is composed of uranium mining, uranium milling into yellow cake, conversion of yellow cake into uranium hexafluoride gas, enrichment of the gas, and fuel fabrication (conversion of gas to solid uranium dioxide, which is formed into pellets and loaded into the rods that comprise the fuel assemblies). The back end of the cycle comprises intermediate spent fuel storage, chemical reprocessing of spent fuel, intermediate waste disposal, waste solidification, and final waste disposal. The technology for all of these steps is, in principle, well-known. The development of the back end of the cycle has occasioned heavy debate in the public policy arena.

During reactor operation, as the fissile isotopes originally placed in the reactor are burned, new fissile isotopes are formed from the fertile isotopes. The rate of replacement is termed the conversion ratio. When the conversion ratio is greater than 1 (that is, the reactor produces more fissile isotopes than it uses), the reactor is called a breeder; when the conversion ratio is slightly less than 1, the reactor is an advanced converter, or near breeder. When the conversion ratio is significantly less than 1, the reactor is a burner, or converter. It is obvious that there are, in principle, a large number of possible reactor types and associated fuel cycles involving uranium, thorium-uranium, and uranium-plutonium mixtures. A few smaller experiments have been carried out on some of these concepts.

The workhorse of the nuclear industry is the LWR, which essentially uses fuel in a once-through mode (no reprocessing of spent fuel). The class includes the pressurized-water reactor and the boiling-water reactor. The Canadian heavy-water reactor, the British advanced gas-cooled reactor, and the Soviet Voronezh reactors have all been commercialized. Breeders are under advanced development.

The impetus for the development of the breeder comes from the recognition that using 10,000 one-gigawatt (GW) LWRs in a once-through fuel cycle mode will exhaust the global uranium supply by 2030. Thus, there have been a considerable number of strategic studies on various rates of introduction of near breeders and breeders into the nuclear economy. Advanced converters and near breeders can stretch out the available resources to late in the twenty-first century.

The real breeder option essentially extends indefinitely on the scale of our concerns.

The issues surrounding the future development of nuclear power are dominated by a series of public policy concerns. They include costs, regulation, safety, risk assessment, waste management, radioactive release, nonproliferation policies, and the future growth of electricity demand. The future of the nuclear option is by no means clear.

Solar Energy

Solar energy is a comprehensive term that encompasses a broad range of processes for converting the heat of the sun into both high-temperature heat and low-temperature heat, electric power, and gaseous as well as liquid fuels. Solar energy systems can range from small systems for individual households to large central station power plants. The average power input from the sun is some 178×10^6 GW, 100,000 times more energy than is now produced in all of the world's power-generating plants. The sun is clearly one of the sustainable resources. Harnessing its energy entails using a disparate set of technologies that are at various stages in the R&D cycle.

Since there are such a large number of solar technologies, it is most useful to differentiate them in terms of three end use categories.

Direct Use of Collected Solar Heat for Heating and Cooling

Technologies that use collected solar energy directly for heating and cooling are designed for low-temperature and medium-temperature processes. Applications are domestic space heating, domestic water heating, and production of low-pressure steam or hot water for industrial and agricultural uses. Active solar systems use mechanically circulated working fluids for heat transfer, whereas passive systems rely on inherent convection, conduction, and radiation processes. These technologies are in use today and provide the closest approach to economic utilization of solar energy. Solar cooling still remains a difficult problem.

Solar Electric Technologies

Electricity generation based on solar radiation can be accomplished in a number of ways. Photovoltaic systems are increasingly promising, though cost and storage remain barriers to further use. Wind-powered generators are technically practical now in certain areas. Solar thermal systems based on focusing the sun's radiation on large boilers have been demonstrated. Ocean thermal energy conversion that uses naturally occurring temperature gradients is a long-range possibility.

Solar Production of Fuels

Production of solid, liquid, and gaseous fuels by using solar radiation as a source has a number of options. Use of biomass for direct burning or synthetic fuel production is relatively near-term. However, in the longer term, photochemical, thermochemical, and electrolytic conversions might offer the exciting possibility of solar-based liquid fuel production. Photochemical conversion involving photolysis, which is the decomposition of water to produce hydrogen, can be accomplished by biochemical, biological, or synthetic methods. Thermochemical decomposition of water to produce hydrogen was first investigated in connection with using the high-temperature heat from nuclear reactors, and processes numbering in the hundreds have been theoretically investigated. The use of solar collectors to replace the nuclear heat source is a challenging basic research task. Electrolytic conversion is based on the concept of using solar-generated electricity to produce hydrogen through electrolysis. The hydrogen can be subsequently converted into methanol.

In summary, most of the solar technologies are, in general, in the early stages of the R&D process. They hold promise in the long term as part of a globally sustainable system.

Geothermal Energy

The source of geothermal heat is thought to be the radioactive decay of elements in the earth's crust. Thus, geothermal energy is one of the long-run candidates for an essentially sustainable energy system. Estimates of total potentially producible thermal energy from geothermal reservoirs of all types average about 100,000 quads, but this estimate is very speculative.

Geothermal energy can be divided into six major categories: hot water reservoirs, natural steam reservoirs, geopressured reservoirs, hot dry rock, normal geothermal temperature gradient, and molten magma. Hot water reservoirs are believed to be the largest part of the total resource, and natural steam reservoirs, the smallest. Geopressured reservoirs are thought to be uneconomic because their temperatures are low and their deposits are too deep. Molten magma has great potential for the far future, but there is no technology now available to exploit this resource. The normal geothermal temperature gradient and hot dry rock processes involve injecting water that can flow in such a way that it can be heated and recovered. This technology is in the early stage of development.

In summary, easily exploitable geothermal reserves have been tapped. Although such reserves are a large potential resource, the technology involved remains for future exploitation after R&D has been done to determine costs and environmental impacts.

Controlled Nuclear Fusion

The basic process of controlled nuclear fusion, involving fusion of light hydrogen isotopes, deuterium and tritium, is well-known. An estimate of the energy from deuterium in the oceans is 10^{12} kW for 1 billion years. Thus, there is promise of an indefinitely sustainable energy source. Research on confining plasmas—highly ionized gases, the natural state of matter at temperatures of 100 million degrees kinetic temperature—is under way in the majority of the developed nations of the world. Plasmas are electrically conductive and thus can be confined by magnetic fields.

Inertial confinement studies are also under way. Steady progress is now being made, and the underlying scientific feasibility of the process is essentially no longer in doubt. The next stage in the development of fusion requires engineering feasibility demonstration devices costing in the range of $2 billion. At present there are no plans for such devices.

The neutrons produced in the fusion process can also be used to produce fuel for LWRs by a hybrid process. One fusion core can supply enough fuel for 10–15 LWRs.

The enormous potential of this technology is sufficient to keep a major worldwide R&D program going. The pace could easily be accelerated if the need arose. Estimates of environmental impact are premature, but educated guesses show favorable impacts.

Energy Efficiency and Conservation

It is difficult to capture the essence of potential technology advances that can lead to increases in energy efficiency, owing to the very diversity that makes conserving energy beneficial. It is, however, abundantly clear that the basic structures are falling into place throughout the various demand sectors for the introduction of new technology devoted to this end. Significant energy savings in the transportation sector are achievable with modest investments in near-term technology for automobiles, aircraft, and freight-carrying trucks. Near-term technology can also have a major influence in buildings and appliances. In the industrial sector, four categories of improvement are noted, namely, introduction of new processes, recycling, improved housekeeping (maintenance, repair, and other measures for curtailing energy waste), and waste heat recovery and insulation.

All in all, the opportunity for significant decreases in the energy/GNP ratio in the industrialized nations of the world is significant. Much of the technology is near-term, but many institutional issues need resolution to permit the favorable trends to continue.

Risk in Energy Systems

There is a clear and growing worldwide concern both for the protection of the environment and for public health and safety. The need to formulate public policy in the energy arena with knowledge of the risks associated with various energy supply options has led to the creation of research programs specifically focused on these issues. The major categories of risk include atmospheric pollution, shortages of water supply, relation to industrial operations, and changes in climate.

Health-related risks—fatal and nonfatal accidents, occupational disease, ionizing radiation, chemical agents, effects of exposure in the various stages of the nuclear fuel cycle, and effects of combustion—have been and will continue to be studied. Catastrophic accidents in large dams, in the use of liquefied natural gas, and in nuclear power plants have been extensively studied. Controversy still exists about these study results, especially in the case of the latter two.

Water, climate, and, to a lesser extent, land use tend to be very big issues potentially affecting large regions of a country and, in some cases, many nations and perhaps the entire world. Acid precipitation, or acid rain, for example, is under intense discussion now, and it is apparent that major research programs are just getting under way to gather information about the necessity of additional environmental controls for fossil-fuel-burning power plants. There has also long been a continuing research program on the effects of carbon dioxide buildup on the earth's climate. In addition, water supply studies, especially as they limit energy availability, have been carried out over the years. Studies of the ecosystem impact of all of the major energy supply options both now and in the future have been carried out.

A general assessment of the current state of affairs indicates that risks in the operation of electric power plants are highest for coal-fired systems, less for oil and nuclear generation, and best for natural gas. In terms of accidents, coal-fired catastrophic failure modes are lowest, whereas there is still a large range of uncertainty in nuclear safety estimates of catastrophic failure. It is believed that the ranges of uncertainty, in toto, involving risks of coal and nuclear power tend to overlap. High-level nuclear waste management needs a more careful study of the effects of long-term, low-level radiation exposure.

The general area of risk assessment and risk management clamors for more careful study and research. It has repeatedly been emphasized that more knowledge is needed about the factors that contribute to public perception of the risks involved in energy systems. If such knowledge were at hand, the acrimony of some of the debates taking place in the public policy arena should be lessened.

ENERGY PROJECTIONS AND THEIR IMPLICATIONS

Energy projections are one road to attempting to understand the significance of future trends in energy supply and demand under the actions of differing energy policies, technological changes, and economic behaviors. It is of interest to note that the complex modeling procedures, whether based on correlation, judgment, expert opinion, or trend extrapolation and whether carried out by government, industry, research groups, or consulting services, tend to cluster or bunch in their results depending on the spirit of the times. As an example, Table 1 illustrates world oil price projections through the year 2000, as given in the various NEPP projections.

TABLE 1. Projected World Oil Prices (1982 Dollars/Barrel)

Projection	1985	1990	2000
NEPP 1979	25	29	41
NEPP 1981	47	55	74
NEPP 1983	26	32	57

SOURCE: U.S. NEPP projections for 1979, 1981, 1983.

TABLE 2. Middle Range of Experts Survey of World Oil Prices (1982 Dollars/Barrel)

Projection source	1990	2000	2010
NEPP 1983	32	57	80
Experts	32	46	65

SOURCE: DOE.

The 1979 projections reflected the occurrence of the Iranian revolution, when U.S. imports were about 8 million barrels per day and OPEC production was over 30 million barrels per day. The common judgment was that prices would saturate at the costs of substitutes, such as shale oil, tar sands, and coal-based synthetic fuels, which were then estimated to be in the range of \$35–\$50 per barrel. It was projected that demand would increase at 1.5–2 percent per year, reaching 70 million barrels per day in 2000.

The 1981 projections were carried out at a time when the Iran-Iraq war reduced OPEC production by more than 6 million barrels per day and spot crude oil prices were somewhat above \$40 per barrel. The OPEC long-range strategy group had announced that it would link prices to OECD economic growth and the behavior of the dollar.

The 1983 picture has again changed drastically. Since 1981, oil prices have decreased, owing to low demand in a time of worldwide recession and drawdown of inventories. Further, non-OPEC production has significantly increased, and oil conservation and fuel switching on a large scale is taking place.

In carrying out the 1983 projections, DOE performed an experts survey of 50 analysts in government, universities, research groups, and trade associations. The middle range of the survey is given in Table 2.

The focus on world oil price trajectories is caused by the heavy weighting and dependence of the energy projection outcomes on this information. Oil is the leading U.S. energy source, currently accounting for 43 percent of present consumption. Moreover, studies by OECD and others indicate a strong correlation between the price of this commodity and the prices of other fuels. In the 1970–1980 period, natural gas prices tracked oil prices on an almost one-for-one basis. The increases in both coal and electricity costs were significant, but not as sharp.

These relationships are relatively easy to understand. Natural gas in international trade must be transported in special ships and requires contiguity of national boundaries for pipeline transmission. Natural gas markets, for the most part, are therefore localized, and the competition for use in such applications as boilers drives natural gas prices toward those of fuel oil. As oil as a primary energy source decreases in use, natural gas will tend to increase in price relative to coal or other cheaper fuels. World coal prices will most probably be set by the cost of providing U.S. coal, since the free-world marginal supply is expected to be dominated by the United States well into the next century, owing to extensive coal reserves. Costs of renewables are much more closely tied to technology and do not depend on a depleting resource base. Prices of electricity should not rise as rapidly as those of oil, since utility feedstocks will be primarily coal and perhaps nuclear in the future.

We turn next to the U.S. energy consumption picture. To describe consumption adequately, the large number of energy services are usually agglomerated into five major categories: residential, commercial, industrial, transportation, and transformation services.

In 1982, the residential sector consumed about 10 quads. Efficiency improvement rates are thought to be such as to yield a slightly increasing trend in total residential energy consumption. Straightforward improved technology is expected to penetrate this market and will involve electric heat pumps, solar space and water heating, and the increasing use of wood and coal. On balance, a continued increase in electricity and renewables use and a decrease in oil, gas, coal, and total energy consumption per household is expected. However, this sector remains a market in which consumption will increase, and the utilities will receive the additional payments for electricity.

In the commercial sector, much of the equipment is now electric, and in response to rising energy costs, energy use per square foot has been declining. The 1983 projections indicate a continuing shift away from oil and gas to electricity.

The industrial sector demand is, of course, closely linked to the economy. The projections indicate that the rate of energy improvement should continue at about 2 percent, resulting from improved efficiency in processes and a change in the mix of products toward those that are less energy-intensive. These factors lead also to a shift toward coal, renewables, and electricity and away from oil and natural gas.

The transportation sector is dominated by motor vehicles. The road miles-per-gallon improvement of 85 percent since the early 1970s translates into about a 2-mile-per-gallon improvement for the entire fleet, owing to slow turnover rates. The average fleet miles per gallon should continue to improve mainly because of technological improvements in mechanical design rather than engine efficiency improvements that are already well established. This sector should not show the increasing demand linked to improvements in the economy that the other sectors are projected to show.

The sector involving energy transformation primarily comprises the utilities and synthetic fuel plants. The utility component of this sector remains financially troubled, but it is trying to respond to the changed situation.

The consumption projections above lead to a description of the kinds of energy, the technologies, and the resources necessary to satisfy the demand for energy. The overall supply issues are discussed below.

Projections of U.S. indigenous oil production show a decline of 1.0–1.5 percent per year over the next 10–15 years if no technology breakthroughs and giant reserve additions are postulated. Alaskan production is limited by the capacity of the pipeline to 2 million barrels per day. The total picture is consistent with the fact that production from reserves has continually outpaced additions to the reserves.

The DOE NEPP projections for natural gas are based on the assumption that the regulatory reform legislation proposed by the administration is approved by Congress. The history of natural gas additions to reserves and production is similar to that of oil additions, with the result that production is expected to decline in the late 1980s. Estimates indicate a decline beyond 1990, after the Alaskan natural gas pipeline is completed.

Coal, which is the most abundant near-term U.S. resource, can serve as a major transition energy source over the next 3 decades. Limitations are mainly environmental and infrastructural in nature. Existing mines and transportation facilities, it is thought, can produce and transport on the order of 1 billion tons of coal per year. The projected 30 percent increase in production between now and 1990 is a major change for the coal industry, but one that is believed to be achievable.

Nuclear power projections are based on plant-by-plant analyses, and even then these estimates can be soft because of the cancellations of plants as much as 30 percent completed, lower recent electricity demand, higher construction costs, and the utilities' financial problems.

The role of renewables in the OECD nations' energy future over the next 2 or 3 decades is still uncertain, owing to cost and technical feasibility uncertainties. Hydropower is limited by site availability. Wood use is growing but will presumably not generate a large market share.

Wind, photovoltaics, and some solar central station generation should appear as increases in the prices of oil and gas in the 1990s begin to drive the market.

The midrange NEPP 1983 projections, which are based on the above remarks, are shown in Table 3. Some of the key assumptions upon which these projections rest have already been noted, i.e., an as-

TABLE 3. NEPP Summary of U.S. Energy Projections Under Midrange Case Assumptions (Quads)

	1982 Estimate	Projected			
		1985	1990	1995	2000
Energy Supplied					
Indigenous Production					
Oil and natural gas liquids[a]	20.6	19.5	19.0	17.7	17.4
Natural gas	17.8	18.9	18.2	17.2	16.3
Coal[b]	18.4	21.3	24.5	28.7	33.6
Nuclear	3.0	4.6	6.5	6.9	7.9
Hydro-geothermal	3.5	3.2	3.4	3.8	4.1
Renewable	2.7	3.0	3.6	4.8	5.9
Subtotal	66.0	70.5	75.1	79.1	85.1
Imports					
Oil	9.0	12.8	12.4	12.4	11.0
Natural gas	0.9	1.2	1.9	2.4	2.6
Coal[c]	(2.8)	(2.8)	(3.3)	(4.4)	(5.4)
Subtotal[d]	7.2	11.3	11.1	10.5	8.3
Adjustments[e]	(0.1)	0.6	—	—	—
Total supplied	73.3	81.1	86.2	89.6	93.4
Energy Consumed					
End use consumption					
Liquids	28.7	29.1	29.3	28.6	27.2
Gases	15.0	17.1	17.6	17.5	17.2
Coal solids	2.8	3.4	3.8	4.3	4.8
Electricity	7.0	8.3	9.4	10.3	11.6
Renewable	2.7	3.0	3.5	4.1	4.8
Subtotal	56.2	60.9	63.6	64.8	65.6
Conversion losses	17.1	20.1	22.7	24.9	27.8
Total Consumed	73.3	81.1	86.2	89.6	93.4

[a]Includes shale oil.
[b]Includes coal used for synthetics.
[c]Indicates exports.
[d]Includes small amounts of coal coke and electricity.
[e]Includes stock changes.
SOURCE: NEPP 1983.

sumed oil price trajectory and implementation of the administration's natural gas legislation. Others that are worthy of particular note are economic growth rates of 3.3 percent in the 1982–1990 period and 2.4 percent in 1990–2000, no changes in tax and environmental policy, and continuation of support for the Synthetic Fuels Corporation at current levels. Note that oil imports in the year 2000 are still projected to be about 5 million barrels per day.

Two other, alternative sets of projections were carried out: one in which economic growth was assumed to be 0.5 percent higher than the midrange case and a second in which economic growth was lowered. The higher-growth-rate case indicates a number of unsurprising trend changes: increased total energy consumption; faster growth in electricity demand, assuming it to be tightly coupled to economic growth; increased oil and gas demand with production relatively constant, resulting in higher imports; and, of course, higher oil prices. In the low-growth-rate case, all of the above trends are simply reversed.

The projections put forth in the OECD's *World Energy Outlook* were based on modeling procedures that were somewhat similar in nature to the DOE calculations. OECD's high-demand scenario envisions economic growth at 3.2 percent per year in the 1985–2000 period, coupled with oil prices that increase only at the basic inflation rate over that period. The low-demand scenario assumes economic growth at 2.7 percent per year and oil prices that reach $45 per barrel (in 1981 dollars) by the year 2000. In the high-demand case, conservation and energy efficiency gains would slow unless new incentives appear through strengthened policies, new technologies, or increasing prices. The OECD study also points out that the high economic growth rates postulated for this case would be needed to reduce the 30 million unemployment level in the OECD countries.

Both the high-demand and the low-demand scenarios anticipate a widening gap between primary and final energy demand. Primary energy use exceeded final consumption by 40 percent in 1980, and in the projections the former exceeds the latter by 55 percent in the 1990s. The major reason is growth in electricity generation, since electricity is both more convenient and more efficient for energy and use. The sources would be hydropower, nuclear, and coal, which, of course, require conversion to electricity for the end use sector.

The OECD study further envisions a stable production regime for oil, with generally shrinking availability. Overall world oil production would likely remain in the neighborhood of 50 million barrels per day.

With OPEC maintaining its share of supply at 50 percent of the market and with a threefold increase in OPEC domestic consumption by the year 2000, the growth in output will have to come primarily from Mexico. The centrally planned economies are postulated to be in a zero trade position over the time period. The OECD countries as a group will, under these scenarios, tend to remain significantly dependent on imported oil. The high-demand case envisions an import level of 30 million barrels per day in 2000, whereas low-demand case points toward 18 million barrels per day.

In its study the OECD made projections about the various energy alternatives. Study results would indicate a stable pattern of natural gas use as a percentage of total energy use. This implies an increasing level of imports and a larger trade in natural gas. At the same time, coal production is projected to expand, and coal use is expected to increase from its current 21 percent to 30 percent by the year 2000. The major increase would come about through electricity generation and other uses in industry.

Nuclear energy is projected to remain below its potential contribution. The oft-repeated concerns about nuclear power would, under these scenarios, limit nuclear use in the OECD to a 10–11 percent share in 2000. This share could well be higher, though, in both Europe and Japan.

Other energy sources for the year 2000 might be expected to account for 10 percent of projected demand, which would be twice its present level. Large-scale hydropower would dominate in the nearer term, and increasing amounts of solar power and biomass power might enter the balance toward the end of the century.

The conclusions of the OECD study indicate that both of the quantitative scenarios represent an unsatisfactory longer-term situation through a reemergence of demand pressures in the oil markets in the late 1980s.

Other, very-low-demand scenarios envisioned are characterized by Lovins as "beyond the pale." Some of these are involved with the "soft" versus "hard" technology controversy; others are labeled "least cost," and still others postulate high levels of penetration of solar and renewable technologies. Although there may in principle be nothing wrong with the bookkeeping that underlies the numbers involved in these latter categories of studies, some are concerned that the social stresses involved in attaining such energy structures are beyond the capabilities of our society to encompass.

SUMMARY

The world today is entering the second decade of a new energy regime following the Arab oil embargo of 1973 and the economic shock of the oil price explosion. Although a new state of equilibrium has not been attained, worldwide changes have occurred—some of them permanent and others perhaps illusory. The oil shocks created an economically paradoxical situation in which both inflation and recession occurred simultaneously and led many of the oil-importing nations to accumulate financial debts that tend to jeopardize the world financial structure. The worldwide recession is in large measure responsible for the present oil glut and the downturn in oil prices. The end result of this turmoil is a situation in which the price of energy, without the effects of inflation, has increased by about a factor of 5 over the decade.

Energy planners disagreed sharply not too many years ago about whether the energy/GNP ratio was rigid or flexible. Those arguments have now vanished as U.S. industry has improved its energy efficiency by about 33 percent between 1973 and 1982, and the energy/GNP ratio has dropped by 19 percent. In the same time period, the world outside the centrally planned economies did almost as well, at approximately 31 percent. One can say that there has been a significant structural change.

Yet another effect whose permanence is far from apparent is a lesser dependence on OPEC oil and its market pricing policies. Expansion of production in other areas, primarily the North Sea, Alaska, and Mexico, have added 6 million barrels per day in non-OPEC production, which it was hoped would lead to further freedom from the OPEC yoke. Some doubt, as our earlier energy demand scenarios illustrated, that this situation can continue. Analysis of the drop in oil demand, crudely speaking, attributes about half of the drop to the recession and half to conservation. As we emerge from the recession worldwide, it is argued that demand will increase, whereas new energy efficiency measures cannot be adopted quickly enough to combat the increasing demand. More quantitatively, a demand increase of 1 million barrels per day translates into a 5 percent increase in demand for OPEC's "oil of last resort." More worrisome is that this translates into a 20 percent increase from Persian Gulf supplies. It is in this sense that one talks of a masking effect in which the market signals do not truly reflect a basic, longer-run serious issue.

Other signs also indicate that all is not well. The debt incurred by the developing countries in paying for their imports has seriously weakened their ability to continue economic growth. The broad "structural" unemployment that is stubbornly showing signs of remaining as the economy improves is thought in part to be a result of the increase in energy prices. The underlying reason is a shift to industries that consume less energy, such as communications and services, displacing the heavier steel and other traditional "smokestack" industries. In addition, growth in labor productivity has been inordinately slow, and one speculation as to the cause involves the substitution of cheap labor for energy-consuming devices.

The implications of the above for energy technology development are multifold. Resolution of the problem calls for a dual approach, involving examination of policies that tend to limit the transition to newer sources of energy as well as appropriate encouragement in the development of these technologies. The basic difficulty lies in the realization that there is an essential paradox at work, since the objectives of protecting the environment and public health, ensuring national security, promoting economic growth, and ensuring equity among nations and classes of people are in conflict.

Examination of energy supply and demand forecasts as well as the underlying technologies demonstrate what has now become widely accepted: we are not running out of energy, but we are consuming energy. To begin the transition over the next decades does not leave many options. The major steps appear to be the following:

- Continue to press on in energy efficiency and conservation technologies. The extension of the life of oil resulting from these actions is significant. Although substantial progress has been made, impressive new opportunities will be available over the next decades as existing capital stock is replaced. Confusing and conflicting market signals should not be interpreted by policymakers as triggers to slow this development. The extent to which the energy/GNP ratio can be lowered without choking off economic development and producing other deleterious effects has been estimated to be a factor of 2. This number is soft and argues for not relaxing efforts on the supply side.
- Continue efforts to enhance fluid fuel supply. This includes efforts at vigorous exploration for conventional oil and gas, pursuit of enhanced or tertiary recovery where applicable, fuel substitution (primarily coal for oil) in central station power generation, and the initiation of development of a synthetic fuels industrial base. Associated

with such a course of action are substantial policy issues involving regulation, deregulation, tax policy, and the like, as well as support for R&D.

• Attempt to pursue a balanced coal and nuclear mix strategy. As fluid fuels phase down in the future, these two technologies, from our current perspective, offer the only hope as economic alternatives for large-scale electricity generation. Electricity demand growth projections have been notoriously wrong in the past. They are highly sensitive to assumed levels of energy efficiency and conservation measures and to future price trajectories of electricity relative to other primary energy sources. The risks and problems attached to these technologies are, as noted earlier, considerable. A balanced strategy, at the least, offers future options for moving away from a set of choices that is too premature. The timing of the need for the breeder on the nuclear side of the equation is certainly not clear at this time. Some sort of technology base program or demonstration program appears to make sense. The contribution of solar, geothermal, and hydroelectric power to the electricity-generating sector appears, on all counts, to be small over the next few decades, but is nevertheless important.

• Pursue a vigorous investment policy in R&D for both the medium and the long terms. The sustainable technologies, namely, solar, the breeder, fusion, and perhaps geothermal, will be the workhorses of the future. The midterm technologies discussed above all need continuing R&D for their improvement.

To carry out a program of the kind envisioned above requires detailed analysis of a number of domestic and foreign policy issues, which will not be attempted in this paper. Some of the more important issues are listed below.

One of the major lessons learned in the 1970s was that tampering with the free flow of the market through mechanisms of regulation of price, allocation of resources, government subsidy to enforce market penetration, and other such measures tends to worsen the problems that the policy is supposed to correct. The market tendency toward equilibrating supply and demand has proven to be a powerful moderating force, and barriers that prevent its natural action should be removed. Institutional barriers, such as building codes, that prevent the application of energy-saving techniques, or tax policies that require too short a payback period, are examples of such concerns.

As noted above, further penetration of electricity is a major avenue for reduction in oil dependence. Because of uncertainties in the future demand for electricity, utilities are in waiting on new investment. The regulatory regime for the utility sector has been at times capricious and ad hoc, and in many instances tariff-setting bodies have made it more difficult for the utilities to obtain adequate financing.

As I have repeatedly emphasized, coal, because of its low cost and abundance, can become an effective substitute fuel. In fact, there are clear prospects for a more global international coal trade regime. For this to occur, a major investment in infrastructure-related items will be needed, such as coal port facilities, coal slurry pipeline legislation, and enhancing of inland transportation facilities.

The acid rain issue is the one receiving the greatest amount of attention in the environmental, technological, and political arenas. Significant reduction in acid rain over the next decade must rely heavily on flue gas desulfurization, commonly called scrubbing. This option is now commercially available but is both costly and environmentally unattractive, since it produces large amounts of sludge. Technical approaches involving burning coal in a cleaner and more efficient fashion at lower cost are clearly to be preferred. Fluidized-bed combustion in one form or another is a technology likely to come along rapidly. Serious attention should also be focused on a possible large-scale measurements program to understand the basic natures of the various components of the acid deposition process and to help in setting standards for impact mitigation.

Natural gas as a resource could be increased significantly before it too begins to wane. It is a desirable fuel in an oil displacement role, but to encourage appropriate levels of market penetration requires detailed attention to pricing policies. In the past, tight controls have inhibited production and encouraged a trend toward oil. International arrangements for long-distance gas pipelines may become more common in the future.

The pursuit of growth in the nuclear sector, as noted above, is almost completely a policy rather than a technical issue. The United States has finally passed nuclear waste legislation, with the result that a demonstration of waste disposal technology under various geological conditions will take place. The policy questions involved are by now so well known that there is little benefit from further discussion here. For a complex of reasons, the current state of affairs resembles a nuclear moratorium in all but name. Utilizing this pause in a positive manner would seem to be a reasonable approach. For example, concepts are beginning to surface for ultrasafe reactors and for schemes whose proliferation resistance is increased manyfold. There is a tendency in the current climate to give such ideas short shrift, with the view that the very existence of new technology concepts somehow casts doubt on the old. The nuclear option might be better served by a relatively inexpensive R&D program focused on innovative concepts and technology fixes.

As this controversy continues, an increasing number of reports predict a bleak future for the nuclear industry in the United States while many other countries press ahead with programs designed to increase their reliance on nuclear power and lessen their dependence on imported oil. France, Germany, Italy, and Great Britain are in this latter category. With the Three Mile Island incident in 1979 and the resulting loss in confidence in the operators' abilities to run these plants safely, the Nuclear Regulatory Commission has put into effect a series of requirements to improve plant safety. As a result of these actions and of the overall climate requiring a long series of steps in the siting and licensing process, the costs per kilowatt produced of nuclear power in the United States are among the highest in the world.

Some evidence indicates that other countries are doing better in this regard. Standardization is one answer that has been offered; it allows a highly competent and experienced team to be assembled for design, construction, maintenance, and training. Fears have been expressed that if the current situation continues for another decade or more, the infrastructure to support the inventory of U.S. reactors may tend to dwindle. Attention to these concerns will clearly continue to be a major energy issue in the future.

The energy supply and demand studies referred to above have tended to show that high-gain breeders, which were once expected to be necessary by shortly after the turn of the next century, will no longer be needed for that role. The likely course of development in the United States will be a technology base program for some time in the future.

It appears, therefore, that the major new requirements for reactors in the near term will all come from the military—for space, for submarine propulsion, and perhaps for materials production for the nuclear weapons complex.

For the very-long-range technologies—breeder, fusion, solar, and perhaps geothermal—the R&D burden has essentially been borne by the interested governments or groups of governments. Under such arrangements, there should not be a loss of essential proprietary information, owing to the very-long-term nature of the research. From the point of view of cost sharing, it is clear that serious international collaboration has many positive virtues. Great Britain has recently announced that it is joining a European-based breeder development program. The European Economic Community has sponsored construction of the multinational fusion device JET. It is a challenge to the decision makers to enhance these collaborative ventures in an arena that is basic to humanity's future.

A technology development that is being discussed in the R&D community and is currently perceived positively in some quarters is the notion of small-scale units that can be modular in nature. Given the large uncertainties the utilities face on both the demand and the supply sides, it is thought that a significant market could exist for economically attractive energy production modules in the tens to few hundreds of megawatts, if they could be developed. Exainples of such technologies are combined-cycle systems, small wind systems, geothermal (where geographically appropriate), photovoltaics, and perhaps biomass. If the United States chose to move its R&D investments into these arenas, it could well capture an international market, since some of these technologies are clearly appropriate for the developing countries.

Although this summary is a much attenuated tour through the worlds of energy technology and energy policy, the very strong coupling between the two should be apparent. Energy planning has fallen into disrepute, and much of the apparatus for examining these issues is being dismantled. The base of support for R&D in energy-related technology has also been whittled away. The world survived the major economic dislocation of the energy-related shocks of the 1970s, but perhaps not as well as some would like to believe. There are some paths through the maze; the world has energy options available to it. The ultimate decisions are, of course, part of the political process. All we need is the vision and the will.

Biotechnology: Status, Forecast, and Issues

Ralph W. F. Hardy

BIOTECHNOLOGY is viewed by many as the next major technological opportunity and has been described as "an infant to be king technology." Actions of international organizations, governments, established industries, start-up companies, the media, investors, universities, and scientists support this view. The selection of biotechnology as one of the six technologies for this symposium further supports this vision, since all of the other included technologies are well-proven in the marketplace. The new biotechnology is essentially unproven. Expectations for the new biotechnology are so high at almost every level—international, national, industrial, and academic—that lack of involvement in biotechnology would be shortsighted. This paper will summarize the status of the new biotechnology, forecast the future, and list issues, some of which are international in character and will have to be considered in foreign relations.

STATUS

Definition

Although biotechnology has become a household word, it unfortunately means different things to different people. The definition used in this paper confines biotechnology to "the use of a biological system to produce a product, the use of a biological system as a product, or the use of the techniques of biotechnology to provide a product, process, or service indirectly." By this definition, biotechnology is an old and well-established technology with many products, processes, and services. For example, biological systems have been used to produce foods and nutritional supplements, such as beer, wine, spirits, cheese, bread, vinegar, vitamins, and amino acids, and pharmaceuticals, such as antibiotics and vaccines. Pharmaceuticals have also been isolated from animal and plant material, for example, insulin and the plant-derived analgesics. In other cases, useful enzymes, polysaccharide gums, organic acids, and solvents are produced by biological systems.

There are also many examples in which a biological system is a product. Most significant are crop seeds (including hybrid seeds), animal breeding stock, semen for artificial insemination, and embryos for transplant in animal agriculture. Seeds and animal breeding stock date back several thousand years, to the early days of agriculture. In addition, microorganismal inoculants—such as rhizobia, for inoculation of legume crops for nitrogen fixation—have been used since the beginning of this century. Other examples are organs for transplants, in vitro-fertilized embryos, and sterile male insects and bacterial insecticides for control of insect pests. Clearly, biotechnology is an important industry that cuts across many areas, but this paper will focus on the new biotechnologies, which for the most part are not yet proven in products, processes, or services.

The Scientific Bases for the New Biotechnologies

There are two major new biotechnologies—genetic engineering and hybridomas for production of monoclonal antibodies—and there will probably be more to come from the expanding thrust in fundamental life science. The scientific bases leading to the generation of these technologies will be reviewed briefly. Several Nobel prizes have been awarded for these key advances, and undoubtedly more will be awarded.

Genetic engineering will be considered first. In 1944, nucleic acids, one of the major classes of polymers in all living organisms, were shown to be the genetic material. This genetic material has a simple alphabet of four chemical units that can be referred to as A, T, G, and C. About 10 years later, the genetic material, which occurs mainly as DNA (deoxyribonucleic acid) was shown to occur as two polymer molecules existing in a double helix. In the double helix, A of one chain binds with T of the other chain, and G of one chain binds with C of the other. There are more than a billion A, T, G, and C units in a single human cell, with a thousand or so A, T, G, and C units arranged in a unique sequence for each gene. This double helical relationship with the above interaction of the genetic alphabet units enables DNA to be self-replicating so that all daughter cells produced from a parent cell will have identical DNAs. In a few cases, such as some viruses, RNA (ribonucleic acid) is the genetic material, with an alphabet of A, U, G, and C. Self-replication of RNA also occurs.

The DNA or RNA is converted to proteins in living cells. Some proteins are enzymes that catalyze the synthesis of the components of cells, others control the differentiation of cells into organs and organisms, and others form part of the structure of cells. Each gene produces a single, unique protein. DNA is converted to proteins via its transcription to an intermediary form called messenger RNA, which is translated to produce proteins composed of 20 different amino acids arranged in a specific sequence for each protein. A, T, G, and C units taken three at a time provide 64 different codons to specify all of the 20 amino acids. There are multiple codons for almost all of the amino acids. In the 1960s, the codons for each of the amino acids were identified. Techniques have been developed to determine the sequence of A, T, G, and C units in DNA reasonably rapidly and of amino acids in proteins somewhat more slowly.

In about 1970, restriction enzymes were discovered in bacteria. Over 100 have now been found. Restriction enzymes cut DNA at a specific site, depending on the sequence of A, T, G, and C units. Other enzymes were found that recombine pieces of cut DNA. This cutting and recombining of different pieces of DNA outside of living organisms—in a test tube—is the basis of the recombinant DNA technique. The use of this recombinant DNA technique to cut and insert foreign pieces of DNA into small circular pieces of DNA called plasmids, and the insertion of plasmids into living cells by U.S. scientists, initiated the era of genetic engineering in the early 1970s. The inserted gene, if it is properly located, enables the recipient, or host, cell to synthesize the protein for which the gene codes.

Hybridomas for monoclonal antibody production will be considered next. Cells originating in the spleen were identified in the 1940s as the synthesizers of antibodies—molecules that selectively combine with foreign molecules or antigens. Antibodies are the key internal defense of animals and humans against invading foreign substances or organisms. Several different antibodies to a single antigen molecule are made by an animal or human, but only one type of antibody, a monoclonal antibody, is made by a single splenic cell. The ability to culture cells from higher organisms, such as plants, animals, and humans, was achieved in the 1950s with the definition of composition of culture media. Normal splenic cells in culture, such as the so-called B cells that make antibodies, only undergo a small number of divisions, about 50, before they die. Transformed or cancerous cells will divide infinitely in culture. Techniques were developed in the 1960s to fuse different cell types. About 1975, an antibody-producing B cell was fused with a transformed mouse cell by British scientists to produce a hybridoma cell containing the capabilities of both parents. These hybridomas produce monoclonal antibodies infinitely.

The New Biotechnologies

Probably the most publicized new biotechnology is the one often referred to as genetic engineering. Genetic engineering enables a directed molecular manipulation of genetic material, in contrast to the random manipulations characteristic of traditional plant and animal breeding. Since it allows manipulation of the genetic material at the molecular level, it is a technology that is applicable to all living organisms—microorganisms, plants, animals, and even humans. It is a dominant technology, since genetic material dictates the capabilities of all living organisms.

The steps in genetic engineering can be described fairly simply. A single virus may contain a few genes in its DNA or RNA, whereas a microorganism may contain several thousand genes and an animal or human cell may contain several hundred thousand genes. In the first step in genetic engineering, it is necessary to obtain the desired gene. This can be done in one of three ways: (1) isolation of the gene from natural material, such as human, animal, plant, or bacterial cells; (2) synthesis of the gene by chemical means, which requires complete knowledge of the sequence of A, T, G, and C units of the gene, knowledge that at this time is only complete for several hundred genes; or (3) in the future by chemical design of genes that have not yet existed in nature but whose product may have characteristics preferable to those made by genes already evolved. The third approach may be viewed as an intelligently directed acceleration of the evolutionary process so as to provide gene products that are more compatible with our current environment and needs in such major areas as health, agricultural productivity, or quality of agricultural products. Most genes are obtained from natural sources. Some have been synthesized, and design has been accomplished in a few model cases.

The desired gene is then placed into a host cell so that the gene is retained and copied in the host cell and functions at a desired rate. Each of these steps is quite challenging but has been accomplished in some cases, such as the microorganismal production of a few human, animal, and plant proteins.

Success in this area is a somewhat random event, since our knowledge of the control of the functioning of genes is very elementary. As that knowledge evolves, we will become much more sophisticated and have greater capabilities in achieving a high frequency of desired results. Possibly one of the most impressive examples of the placing of foreign genes into a host cell, with the genes being retained, copied, and kept functioning, is the introduction of additional genes for growth hormone into the embryos of laboratory rodents. The rodents that develop from these embryos grow up to double the size of their littermates without additional growth hormone genes. Host cells can be a variety of cells, including, in theory, microorganism, plant, animal, and human cells. One can suggest that we may make synthetic cells into which genes will be placed. It is important ethically to differentiate between genetic engineering in which foreign genes are introduced into human somatic cells, whose progeny are confined to this generation, and genetic engineering in which foreign genes are introduced into human gametic cells, which will affect future generations.

A second important new biotechnology is the broad area of plant, animal, and human cell and tissue cultures. This broad area is probably at least as important as genetic engineering, but at this time it is a less developed technology. With these techniques, one can culture plant, animal, or human cells and tissues in a test tube or fermenter tank just as one cultures microorganisms. In many cases, it is desirable to regenerate the whole organism from the single cell. However, at this time, single cells of only a few plants—tobacco, carrots, and some of the horticultural crops—can be regenerated to whole plants. Unfortunately, regeneration has not yet been reproducibly accomplished for most of the important agronomic crops, such as wheat, corn, and soybeans. In time, empirical systems to achieve this goal will be developed for all plants, and it is reasonable to expect development of the capability to regenerate organs, and maybe even complete organisms, from animal and human cells. Such achievements in the animal and human area are quite distant.

The most important new biotechnology in the cell and tissue culture area is the generation of hybridomas for producing monoclonal antibodies. Hybridoma monoclonal antibody biotechnology is producing products that are important for research and use in purification processes, as veterinary pharmaceuticals, and as in vitro diagnostics. Monoclonal antibodies are expected to be used as in vivo diagnostics and as targeted delivery systems for therapeutics.

The development of additional biotechnologies is expected over the next years and decades. These technologies will evolve from the expanding fundamental studies of such areas as embryology, immunology, neurosciences, and plant sciences. What is the molecular basis of memory? Undoubtedly, that understanding will reveal new biotechnologies that are as important as or more important than those revealed by the molecular understanding of genetics.

General Characteristics of the New Biotechnologies

The new biotechnologies are products of scientific advances in molecular biology mainly in the United States and Western Europe. Although the techniques have been described in a fairly simple manner, their use, in general, is quite sophisticated and requires a high level of skill by the research and development (R&D) scientists. It is anticipated that those who manufacture products of the new biotechnology will probably be fairly small in number and less sophisticated than the R&D component, whereas the delivery group will have fairly sophisticated skills because of the anticipated multiplicity of products and the need to educate the user, as occurs in the pharmaceutical business.

The new biotechnologies are, as described, only techniques, and their use will depend on interactions with other areas of science, especially the life sciences. Many existing industries are expected to be affected broadly by the new biotechnologies, as will be described in some detail in "Forecast," below. These impacts may provide solutions to some of the world's most pressing problems, e.g., cancer in the health care area and adequacy of the food supply in the agricultural area. Several common characteristics of the new biotechnologies are described below.

Commercial Impacts

One expects these biotechnologies to generate products. Initially these products will be protein molecules, because the first products of the genetic system are proteins. Subsequently, other molecules will be synthesized by a variety of proteins collectively functioning as enzymes to produce nonprotein molecules, such as antibiotics. These new biotechnologies are expected to produce biological systems that are products. Examples include cells, tissues, seeds, and, in time, organs and maybe whole organisms.

Understanding biological systems generated by these biotechnologies will probably lead indirectly to more important products and processes than will the above direct applications. Examples of such understanding include recognition that genes are not stable but rather are highly mobile, identification of oncogenes and the growing evidence of their involvement in the cancer process, and understanding what controls genes, what turns them on or off for making their protein products. At any one time, only a small fraction of genes in a cell are turned on. The chemical products that may result from this understanding of gene regulation may be important in the future as synthetic agrochemicals and pharmaceuticals for timely turning on and off of genes consistent with the desired control of disease, mood, behavior, yield, and quality.

The new biotechnologies have almost unproven commercial impact outside of the small research product area. Exceptions to this statement are Humulin® (human insulin), Genecol 99® (monoclonal antibody as a prophylactic for calf scours), porcine antineonatal-diarrhea vaccine, hepatitis B core antigen, and some monoclonal antibodies used as diagnostics. Sales from the new biotechnologies are small and probably only in the area of a few hundred million dollars, at most, for 1983. Various estimates have been made of how annual sales will grow, and a reasonable estimate may be $1 billion by 1990, $10 billion by 2000, and more than $100 billion by 2025. These numbers are substantially more conservative than some of the most optimistic reports, where sales in excess of $100 billion have been proposed by 2000.

Proprietariness

Proprietariness is critical for success in the new biotechnologies and must be viewed as unestablished at this time. Unfortunately, many commercial firms are working on the same potential products, such as interferons, interleukin II, growth hormone, and hepatitis vaccine.

Of significance was the Supreme Court ruling in 1980 that permitted for the first time in the United States the patenting of novel life forms as new compositions. How that ruling will be extended and upheld remains to be seen. Moreover, many of the health care biotechnology products are natural products that, by definition, already exist in nature. It is unclear what the patentability of these compositions will be when they are produced by the new biotechnologies. The number of antibody possibilities is so great in the hybridoma monoclonal antibody area that definition of useful proprietariness will be difficult.

Safety

The new biotechnologies—and, specifically, genetic engineering—were viewed shortly after their origin in the 1970s as presenting great potential hazards to laboratory workers and the environment. Extreme caution was recommended. The outcome provided a model demonstration of how to proceed in a new scientific area where the risk is unclear. A cautious combination of physical and biological containment was used in the initial stages, with some areas of experimentation forbidden. As knowledge accumulated to suggest that the hazards were minimal or almost nonexistent, these guidelines were modified in steps to match the reality. The key was for the scientific community to take the lead and regulate itself, with the National Institutes of Health (NIH) establishing guidelines. These guidelines were flexible to be consistent with the risk, in contrast to congressionally established, relatively inflexible laws that would slowly respond to changed perceptions of risk. The NIH Guidelines for Recombinant DNA were initially applied to research done at and/or funded by NIH. Other U.S. governmental agencies made the NIH guidelines applicable to their activities. Industry was provided the opportunity for voluntary compliance, which to my knowledge has been followed by all industry. As the knowledge accumulated to show considerable natural mobility in genes, and since no significant health hazards were found, the guidelines were adjusted so that most recombinant DNA experimentation today is possible in a standard laboratory. Now, the major concern has transferred to the environmental effects of genetically engineered organisms released outside of the laboratory.

Ethical Concerns

Ethical concerns have been generated by the new biotechnologies, especially genetic engineering. These concerns are understandable, since genetic engineering enables the manipulation of all genetic material. In general, society appears to be comfortable with human or animal proteins produced in microorganisms for use in treating animal or human disease or in improving animal productivity. Society is much less comfortable with the manipulation of the human genome. Such experiments are already possible or will be in the near future, based on the super-rodent growth hormone experiments. A meaningful dialogue among scientists, physicians, and the rest of society will be needed before such experiments will be permitted, even though they may result in improved health or longevity for the recipients.

The reactionary view of some segments of society regarding genetic engineering is documented by the recent legal action by a group to prevent the release of a genetically engineered microorganism into the environment to evaluate its ability to decrease crop injury due to freezing. The case concerns a parent microorganism that occurs naturally and produces a protein that promotes the formation of ice crystals. This microorganism was engineered by removing the gene that produces the protein that causes nucleation of ice crystals. The group's legal action to prevent field experimentation is unusual in that the group objects to the absence of a gene rather than to the addition of a gene, and it probably is an indication of society's poor understanding of genetic engineering. Furthermore, agriculturalists have for centuries been selecting crops and animals with improved genetic makeup for productivity, disease resistance, or quality of product. These traditional breeding experiments involve massive recombinations of genetic material, whereas genetic engineering enables the addition of a single identified gene or, as in the above case, the deletion of an identified gene. It would seem logical that the new biotechnology, which defines the gene changes, should produce less societal concern than the old biotechnology, with its many undefined gene changes. Education of society's leaders is essential for enabling many of the benefits of genetic engineering to be delivered.

Expectations

Excessive expectations by almost all sectors of society have been created by the new biotechnologies. Strong promotional activities by the media, society's interest in living organisms (especially the human ones), and industrial and government interest in high technology have generated these expectations. Excessive expectations are at the international, national, state, and even, in some cases, city levels. One is perceived to be second-class if one does not have a significant activity in the new biotechnologies. Moreover, the public, industry, the investor, and the scientist have excessive expectations. For example, the public expects products of biotechnology to have major beneficial impacts in health care. Two or three years ago, the public was led to believe that interferon would be the "silver bullet" that would cure all forms of cancer. That expectation has not and will not be met.

Companies

Start-up companies have been established to exploit the new biotechnology. Many involve key scientists in consulting or equity roles, so that the number of neutral, unattached, academic scientists in biotechnology-related science areas has decreased substantially. Established industries have become involved through equity positions in small companies, contracts with universities, and establishment of internal capabilities. An excess of venture capital and private investor funds has generated and still maintains a large number of start-up companies, although only a few of these large number of companies have or will have in the foreseeable future significant profitable sales from biotechnology.

The rapid growth of the area has created deficits of adequately trained people in some fields. An example is biochemical engineering, which combines the process skills of chemical engineering with the molecular biological skills of genetic engineering. These skills are essential for developing processes and for enabling their scaleup to make many of the new biotechnology products.

Competitive Position

A major report was recently published by the U.S. Congress's Office of Technology Assessment (OTA). This report focused on the world competitive position of U.S. biotechnology. This is the second report by OTA on biotechnology in recent years and documents the support and concern of the U.S. government for the successful development of the U.S. biotechnology industry.

In the broad area of the new biotechnologies, the United States is clearly the leader at this time. This leadership has been facilitated by a supportive government environment that includes the NIH guidelines with no new laws, the OTA reports, R&D tax credits, R&D limited partnerships, and activities by other government departments, such as the Department of Commerce. In the United States a large number of biotechnology specialty firms were initially capitalized through venture capital or equity financing or both by established firms. The market capitalization of such firms is probably in excess of $3 billion. There is also a growing use of R&D limited partnerships to assist financing of the research and costly clinical trials to develop biotechnology-generated therapeutic products. In addition, many established companies have both internal and external activities. These include the major chemical, pharmaceutical, energy, food, and other companies. Trade organizations, such as the Industrial Biotechnology Affiliates, have been formed to promote the common interests in biotechnology of both start-up and established companies.

Several states—Maryland, Michigan, Minnesota, New York, North Carolina, and Ohio—have set up programs to position themselves strongly for the anticipated biotechnology industry. In the Washington, D.C., area, a novel combination of industrial firms, a university, and government at the federal, state, and local levels has created a new advanced biotechnology center.

There is also expanded support of U.S. universities by mainly U.S.-based industry. Some of this support involves contracts to do specific tasks, and some of it involves broad multimillion-dollar relationships with various degrees of control by and rights for the industry. There is one significant example of a foreign company, West Germany's Hoechst, that has a contract to provide the Massachusetts General Hospital with about $70 million over the next 10 years to support research relevant to the new biotechnology. Concern has been expressed that these major arrangements may adulterate the scientific research and training activities of major U.S. academic institutions.

Great Britain, France, Germany, Switzerland, Australia, and Canada have developed thrusts in biotechnology that, in many cases, involve government-financed start-up companies with financing also from the private sector. Examples include Celltech in Great Britain, which was established with rights of first refusal to inventions made in research funded through the Medical Research Council, and Great Britain's recently established U.K. Agriculture Genetics Company, which has similar rights to research funded by the Agricultural and Food Research Council. Transgene is an example of this type of company in France, and another is Canada's Allelix, which has been promised funding of about $80 million. The recent OTA report concludes that Western Europe has not been highly successful in establishing its biotechnology thrust.

Many consider Japan the major potential competitor of the United

States in the new biotechnologies. Japan is working aggressively to catch up on the technology, but in general does not have a strong scientific base to underpin it. Government support facilitates the establishment of biotechnology in Japan, and many large companies have established biotechnology subsets. Japan is licensing technology especially from U.S. start-up companies. One Japanese firm has even established a laboratory in the Washington, D.C., area with the obvious hope of being able to couple directly to this strong biotechnological-scientific community. The number of Japanese firms that have indicated activity in interferon is an example of Japan's aggressive attempt to establish itself in biotechnology. The Japanese government has indicated that it considers biotechnology the next major technological opportunity.

The centrally planned economies, such as those of the Soviet Union and China, do not have a strong technological or scientific base for the new biotechnologies. China is moving to establish biotechnology and strengthen its weak scientific base. There do not appear to be strong thrusts in biotechnology in the Soviet Union, although recent reports suggest work to create organisms for military purposes.

Many of the products of biotechnology will be applicable to developing countries. The National Academy of Sciences held a workshop in 1982 on priorities in biotechnology research for international development and identified several areas where biotechnology should have an impact on development in these countries. Discussions have been held regarding the establishment of an international center for genetic engineering and biotechnology. The center will be located at two sites, New Delhi and Trieste, with major funding by both India and Italy. The next section will attempt to forecast the industries that will be affected by the new biotechnologies and the nature of that impact.

FORECAST

The pervasive nature of the new biotechnologies suggests that they will affect many industries. These industries range from the most obvious of health care, animal and crop agriculture, and food to others, like industrial chemicals, energy, forestry, pollution control, mining, and, in the more distant future, bioelectronics and information. Most of these areas are being investigated, with probably the greatest emphasis at this time on health care (followed by agriculture) and the least emphasis on bioelectronics. An indication of the timing of significant initial impact and the extent of impact expected at maturity (the

TABLE 1. Biotechnology Impact Analysis[a]

Industry	United States	European Economic Community	Japan	USSR	China	Developing Countries
Health care	4.3	4.2	4.4	3.3	3.2	3.1
Agriculture	3.7	3.6	3.7	3.1	3.1	3.2
Forestry	3.1	2.7	2.2	2.3	2.3	2.5
Food ingredients	3.3	3.3	3.6	2.7	3.0	2.7
Industrial chemicals	3.5	3.3	3.7	2.6	2.5	1.9
Energy	2.9	2.9	3.1	2.2	2.3	2.1
Pollution control	3.4	3.3	3.5	1.9	1.9	1.5
Mining	2.6	2.2	1.9	2.3	2.1	2.1
Bioelectronics	3.3	3.0	3.5	2.4	1.8	1.3

[a]Impact Expected by Year 2030: 5 = Very High, 4 = High, 3 = Moderate, 2 = Low, 1 = Very Low

Year by Which Significant Impact Is First Felt

Industry	United States	European Economic Community	Japan	USSR	China	Developing Countries
Health care	1990	1990	1990	1998	2002	2005
Agriculture	1996	1996	1998	2002	2005	2008
Forestry	2008	2009	2011	2013	2017	2020
Food ingredients	1997	1997	1998	2005	2007	2010
Industrial chemicals	1999	2000	1997	2006	2011	2016
Energy	2019	2010	2008	2014	2016	2020
Pollution control	2002	2002	2002	2015	2018	2023
Mining	2009	2012	2015	2016	2017	2021
Bioelectronics	2010	2011	2007	2019	2023	2029

SOURCE: R. M. Busche, E. I. duPont de Nemours & Company.

year 2030) from biotechnology in each of these areas is shown in Table 1. These data were generated by 50 people knowledgeable in biotechnology, with half from industry and half from academe. Agreement between the averages for the two groups was high. Each of these industries will be examined to indicate the nature of the products, processes, or services and the specific biotechnological characteristics for that industrial area.

Health Care Products

Products of biotechnology for many health care areas can be suggested: therapeutics, vaccines, diagnostics, delivery systems, prostheses, transplants, and gene therapy. In therapeutics, regulatory peptides and proteins are the most obvious products. They include insulin, interferons, interleukins, growth hormone, tissue plasminogen activating factor, blood factor VIII, and others. Considering that the human genome can make some 100,000 proteins, many of which probably function in regulatory roles, it is reasonable to suggest that many protein products will be possible, some of which will become commercially useful and many of which will provide important scientific understanding. These regulatory proteins or peptides will probably be found to be useful in the treatment and prevention of cancer and cardiovascular, immunological, metabolic, respiratory, infectious, reproductive, neural, and aging diseases. The breadth of their potential therapeutic impact on disease is awesome. Undoubtedly, the pharmaceutical industry will be revolutionized in time by these products or processes or by those based on the understanding that these molecules generate.

Vaccines will also be greatly affected by the new biotechnologies. Vaccines can be visualized for the uncontrolled areas of hepatitis, influenza, mononucleosis, and herpes and other sexually transmitted diseases, all problems in the more developed world, and also for malaria, cholera, and parasites, which are concentrated in the developing world. The opportunity exists to make synthetic vaccines by these technologies so that the quality of the vaccine product will be improved and the contaminating material in the vaccines will be eliminated, thus decreasing the side effects. It is reasonable to suggest that the above-listed diseases may become as unknown as smallpox, which traditional vaccines have eliminated. Maybe even the 100 or so common colds experienced by each of us during his or her lifetime will be eliminated by a vaccine resulting from biotechnology.

Diagnostics are already being marketed that are based on the hybridoma-monoclonal antibody techniques, and specific probes based on information generated in this area are expected to allow the early diagnosis of major genetic diseases. It may be possible to identify at an early stage individuals at risk over their lifetimes to such diseases as cancer and cardiovascular disease. Such individuals could take steps to minimize their exposure to risk-elevating environmental factors. Clearly, the diagnostic impacts could be major.

Systems to deliver therapeutics to desired sites within the body are expected from the new biotechnology. A monoclonal antibody that interacts with a cancer cell could be an ideal carrier for delivering a toxic substance, such as a drug or radioactive material, to the tumor. This selective delivery would decrease side effects. Generic drugs could become proprietary through a coupled delivery system. Other delivery systems may involve plasmids, biopolymers, and liposomes, all or part of which may be products of the new technology.

In the more distant future, the new biotechnologies may be utilized to produce prostheses and maybe, eventually, organs for transplants. The achievements in these areas will depend upon major advances in human cell and tissue culture.

Gene therapy could become a reality in the near term, but it is doubtful that society will be comfortable with such therapy for some time. The successful rodent growth hormone experiments document the reality of gene therapy. It would seem reasonable that in time an informed society would view as highly desirable the use of gene therapy to treat embryos from parents with a high likelihood of transmitting genetic disease. However, society will probably disapprove of gene therapy for changing characteristics, such as stature, hair color, skin color, and related phenomena, that are not critical to improving an individual's health.

The science and technology base for the new biotechnology in health care is now predominantly in the United States, followed by Europe and then by Japan, which is significantly behind but is aggressively trying to establish health care biotechnology. The relative inability of Japan to establish a world pharmaceutical business may be indicative of its ability to develop a biotechnology health care product base. The science-technology bases in other countries, such as the Soviet Union and China, are much behind those listed so far, and the developing countries are even farther behind.

Most analysts suggest that the initial and largest impact of biotechnology up to at least the year 2000 will be in the health care area. This statement is consistent with the products in the market and the potential products in clinical trials. In the long term, biotechnology is expected to provide products for all areas of health care and almost all diseases. Regulation will be high, as it is for other health care products, and at this time a biotechnologically produced product is subjected to an evaluation as rigorous as that for a new synthetic pharmaceutical. Experience with biotechnology products may in time lead, on the one hand, to decreased regulatory requirements or, on the other hand, to increased regulatory requirements. One major concern is the presence of foreign microorganismal proteins as contaminants of human proteins produced by microorganisms. Other concerns are about the stability in foreign organisms, such as microorganisms, of the gene for human proteins and about the possibility that minor gene changes will lead to protein products with minor alterations, which may have significant immunological or toxic effects. A cautious approach is appropriate at this time to build up a base of experience that will lead to an appropriate regulatory stance.

There is potential for biotechnological health care products in both developed and less developed countries. The specific needs differ, and at this time almost all of the emphasis is on developed countries where there is the opportunity for economic return to justify the R&D expenditures. Clearly, society will have to support biotechnology efforts focused on developing countries.

The health care products from biotechnology will be largely new products having improved efficacy for existing markets or first products for new markets that are not yet satisfied by existing products, e.g., cancer and immunological diseases. These new products for existing markets may be provided at lower costs, but the experience with human insulin does not assure that this will occur.

There was an initial expectation that biotechnology would provide a few billion-dollar products for health care. Interferon was one of the first examples that was expected to produce more than $1 billion in sales. As clinical trials for interferon have progressed, its role as an anticancer agent has narrowed substantially. Other products will probably experience a similar narrowing in potential market as knowledge expands. One may suggest that the market size may average $25–$100 million per product and that there will be a large number of products with modest sales volumes.

There are many potential products on which R&D is being conducted at this time by both start-up and large chemical and pharmaceutical companies. Moreover, many of the companies are pursuing identical products, resulting in considerable expenditures for a single potential product. Interferon is an example of a product that has been pursued by many companies. More dollars may have been spent in recent years on development of interferon for therapeutic use than on the development of any single pharmaceutical to date. Such multicompany expenditures may be justified in this case because of the experience they have provided in this new technology. Obviously, there is now a need to broaden the product objectives if more than a few companies are going to be successful in health care biotechnology.

The health care products will probably, in time, substantially decrease death from cancer and cardiovascular disease and consequently significantly lengthen human life span and increase world population. The multiplicity of products that are possible may increase the cost of health care because of the many new treatment options that will be provided, but it may decrease the overall cost of health care because expensive hospital care for untreatable terminal diseases, such as cancer, should be decreased. Overall, the impact of biotechnology on health care appears to be extremely important, but because of the absence of significant products that are yet proven in the marketplace, it is too early to assess the real impact.

Agriculture

Agricultural Animals

New biotechnologies are expected to affect a number of areas of animal agriculture. Vaccines and diagnostics are probably the first examples. Monoclonal antibodies to diagnose bacterial, metazoan, protozoan, rickettsial, and several viral diseases would be useful. For animal diseases, diagnostic reagents are needed for identifying infectious agents accurately. Diagnostics could also be used to assess the quality of animal products. Developed or potential vaccines for foot-and-mouth disease, neonatal diarrhea, bacterial respiratory disease, coccidiosis, parvovirus, heartworm, Newcastle disease, African swine fever, hemotropic disease, and tuberculosis would be important for developed and developing countries. Initial examples are already in R&D or in the marketplace. In one example, a monoclonal antibody to a bacterium that causes calf diarrhea has been approved for marketing. This material is called Genecol 99®.

The next area to be affected may be veterinary therapeutics. Animal interferon may be used for treatment of viral diseases in domestic animals and pets. Other therapeutics may be developed that will probably evolve from studies in the human health care area, just as veterinary pharmaceuticals have evolved mainly from human pharmaceutical R&D. In biotechnology, the specific product may be based on the form of the molecule occurring in the animal. Bovine interferon for treatment of shipping fever in cattle may be an example.

Biotechnology products to improve production efficiency in animal agriculture are expected. Already, bovine growth hormone made by genetically engineered microorganisms is being evaluated. For example, experimental injection of growth hormone into dairy cows has increased milk production by 20–30 percent. It is doubtful that multiple injections of protein molecules, such as growth hormone, will prove to be practical. Delivery systems that will allow feeding or a single treatment that will last for an extended period will have to be developed.

As indicated earlier, gene therapy works in rodents, and tests are in progress to extend these observations to domesticated animals, with success expected within the next year. This approach to generating additional growth hormone in an animal appears to be preferable to microorganismal production coupled with multiple injections. Gene therapy may be the most important impact of the new biotechnology in animal agriculture and should lead to increased growth, improved feed efficiency, improved quality, and maybe even new capabilities in domesticated animals. However, it will have to be done so as to maintain the balance in metabolic systems. The impact of this area on animal agriculture could lead to further excess production capabilities in the United States and Europe, compounding, for example, the excess production capability of the dairy industry.

Agricultural Crops

In the shortest term, the new biotechnology should produce more effective microorganismal soil inoculants. These may be *Rhizobium* inoculants with improved nitrogen-fixing efficiencies for legume crops. *Azospirillum* with improved nitrogen-scavenging capabilities for grain crops, and mycorrhizas that are more useful in phosphate scavenging. These applications are based on microbial genetics, which is a much more developed technology than is plant molecular genetics. Consequently, the progress should be reasonably rapid.

The new biotechnology may be used to detect latent or unexpressed disease in plant breeding material. Here, probes to the disease enable detection of the latent disease genes and thereby eliminate multiple growth experiments in which one waits to see expression of the disease. This approach should significantly decrease the time required in traditional plant breeding to test genetic materials for latent disease. Other diagnostics to monitor disease and insect infestations may be useful to guide field treatments more objectively.

Biotechnology is expected to play a role in the production of crops. The microorganism *Baccilus thuringensis* is used commercially as an insecticide, and improvements in this or other microorganismal systems may expand biocontrol agents for insects and possibly even diseases and weeds. Biotechnology may even assist in the protection of plants against physical stress, such as freeze injury.

The major impact of biotechnology on crop agriculture will be in the area of genetically engineered seeds. Not all of the technologies necessary for broad success in this area are in hand, because they will probably require a combination of genetic engineering technologies and plant cell and tissue culture technologies. This suggests that we should not expect major impacts in the short term. The types of genetically engineered seeds may follow the following sequence: Initially, single genes will be introduced into plant cells. These single genes may provide resistance to agrochemicals, such as herbicides, or result in the production of seed proteins with improved quality. Subsequently, characteristics that require multiple genes will be introduced. These genes may give resistance to soil stress (such as aluminum toxicity, which is common in many South American soils), environmental stress, and stress due to insect and disease.

Of even more difficulty but of greater impact will be genetic engineering to produce seeds with increased yield capabilities. Examples here may be the manipulation of genes to improve the photosynthetic process and the partitioning of the sucrose product of photosynthesis between the harvested part of the plant, such as seeds, and the unharvested residue. Our knowledge is quite underdeveloped in identifying the proteins and genes that will be important in this area, although the most abundant enzyme in the world, the carbon dioxide-fixing enzyme, may be a key opportunity where successful biotechnological approaches might produce up to a doubling in yield of major crops such as soybeans.

In the more distant future, plants will be genetically engineered to give them new capabilities. The most publicized capability is genetically engineered plants that meet their need for the essential nutrient nitrogen through the process of biological nitrogen fixation. The complexities of the genetic system, the sensitivity of the enzymatic nitrogen-fixing process to the oxygen in air, and the huge energy consumption by the biological nitrogen-fixing process suggest that it will be a long time before nitrogen self-sufficiency will exist for high-yield crops. Nitrogen self-sufficiency in lower-yield crops, such as those in developing countries, may be more quickly achieved. In another area, artificial seeds will be produced in which embryos will be encapsulated in a coating that will allow them to cope better with the hostile environments into which seeds are placed.

Overview of Agricultural Biotechnology

Overall, the science-technology base for agriculture is substantially weaker than that for health care, reflecting the small R&D investments in agriculture in recent decades. The science-technology bases are equivalent for Western Europe, the United States, and Australia. Much weaker than these three leaders is Japan, whose base is more solid than that of the Soviet Union (which has a better base than do the developing countries). The relatively strong position of Australia reflects its strong R&D investments in the plant and animal sciences through the Commonwealth Scientific and Industrial Research Organization. In fact, the two leading comprehensive centers for plant science research related to biotechnology are located in Australia and Great Britain, and (surprisingly) not in the United States.

Biotechnology appears to be able to generate products for most needs of animal and plant agriculture. Regulation of such products will be less demanding and time-consuming than that of products for health care. (Contrast the rapid movement of Genecol 99® to approval for animal agriculture versus interferon for human therapy.)

Agricultural biotechnology products have potential for both developed and less developed countries, and the ultimate impact may be greater in less developed countries than in developed ones. The products are expected to increase productivity substantially, decrease the cost of production, reduce vulnerability to stress and disease, and expand the world's useful crop land.

Of some concern is the hypothesis that the overall ultimate impact of biotechnology could decrease substantially the competitive advantage of U.S. production agriculture over that of other parts of the world, such as the Soviet Union and the Southern Hemisphere. A major current competitive advantage of U.S. crop production is the favorable climatic and soil environment—temperature, rainfall, and high-fertility soils. Biotechnology may decrease the vulnerability of crops to water and temperature stress so that countries like the Soviet Union can produce consistently higher yields and in time even approach self-sufficiency or become exporters. This conclusion will require a much more aggressive Soviet biotechnological and agricultural system than now appears to exist. Much of the soil in the Southern Hemisphere suffers from aluminum toxicity, which limits phosphate uptake. In this case, biotechnology may produce plants or microorganismal inoculants that enable more effective scavenging of phosphate in high-aluminum soils.

Biotechnology could make South America an even more significant producer of grains and thereby a more formidable competitor of U.S. crop production agriculture. A similar scenario might be proposed for Africa's animal production, where biotechnology may decrease animal diseases and enable Africa to develop a possibly significant meatpacking industry. The above scenarios are presented as hypotheses, but hypotheses with such significant impacts that they must be considered.

Gene therapy, based on the multiple successes with rodents, must be judged as imminent for domestic animals. The impact could be huge increases in the efficiency of production by swine, dairy and beef animals, and poultry.

Biotechnology research in the agricultural area is being conducted by a few start-up companies and several established chemical, energy, and plant-breeding companies. Already, a few animal products exist in the marketplace for use mainly as preventive agents for animal diarrhea. The area is expected to develop more slowly than health care. The ultimate impact is expected to be great, but because of the small number of commercial products, it is too early to assess the actual impact.

Food and Food Additives

Biotechnology—for the most part not new biotechnology—is being used to produce single-cell proteins. The majority of single-cell proteins have been developed for use as animal feeds, such as Purteen®, made by bacteria that use methanol as their raw material. This product is manufactured in a continuous fermenter designed by the John Brown Engineering Company in Great Britain. It is the largest continuous fermenter, challenging the often-stated view that the Japanese are the world leaders in bioengineering. Other single-cell proteins include a product, mycelium, made by a fungus that uses the glucose from starch as a substrate. This material has been developed as a human food. Several meat analogues have been test marketed. Clearly, single-cell protein production for food as well as feed is technically feasible. Its success will depend upon comparison of its economics with crop and animal-produced foods.

Other food and food additive areas expected to be affected by biotechnology include amino acids, sweeteners, enzymes, vitamins, flavorings, and colorants. The amino acid phenylalanine, at least some of which is produced by a new biotechnological process, is used to make the sweetener aspartame. Undoubtedly, there will be other significant impacts in the food area, but the base of scientific activity in this area is somewhat less than that for those areas previously discussed.

Industrial Chemicals

Industrial chemicals are, for the most part, much lower in price per unit mass than are health care, agriculture, and food products. As a result, the processes needed for favorable biotechnology economics will be critical. The fermentation of renewable resources, such as glucose from starch, to ethanol is now competitive with industrially produced ethanol based on ethylene. Most other chemical feedstocks are not yet competitive, and the timing of competitiveness will depend to a large extent on fossil fuel prices and advances in developing new biotechnological processes. In time, biotechnology will be used to produce a variety of oxychemical feedstocks, including (in addition to ethanol) acetic acid, acetone, *n*-butanol, isopropanol, glycerol, adipic acid, phenols, and aromatics. Feedstocks, such as ethylene and butadiene, that may be obtained from ethanol are in the more distant future, probably after the year 2000, based on the much slowed projections for increases in fossil fuel prices.

It is also anticipated that specialty chemicals and polymers will be made by biotechnology. Already in the marketplace is microorganismally produced poly-β-hydroxybutyrate, marketed as Biopol®, a specialty polymer. Other biopolymers or chemically modified biopolymers are expected, as they are more thoroughly explored, to show advantages over those that are now available via synthetic routes. For example, bacterially produced celluloses may have properties, such as strength, superior to those available from the best synthetic polymers. Methyl glucosides are now being produced from starch for use in making polyols for rigid urethane foams.

Industrial enzymes will also be made by biotechnology. These may include proteases, glucose isomerase, rennet, trypsin, and others. Of these, rennet for cheesemaking has been made by the new biotechnology.

Energy

Biotechnology may affect the huge energy field in several ways. With respect to fossil fuels, the products of biotechnology will be used to enhance oil recovery. The product types include biopolymers and biosurfactants. The markets could be very large, but the economics here will depend almost exclusively on the price of oil.

Biotechnology may be used to improve ethanol production where ethanol is now used as an octane enhancer for gasoline. Biotechnology may also improve the production of energy crops to make them more economical. Examples might include latex from guayule, euphorbia, or milkweed: oil from jojoba, tallow tree, or buffalo gourd; and biomass from sugarcane, poplar, pine, eucalyptus, and others. If U.S.

crop agriculture loses a major portion of its competitive advantage in the longer term, it may be desirable to develop energy crops as an alternative to the commodity grains that now dominate these agricultural acres.

Forestry

Biotechnology could, in the long term, produce major beneficial impacts in forestry. However, such benefits will probably be slow in coming, because the research base is relatively small and the time involved in growth of forests is relatively long. One can suggest that new tree varieties will be produced by using tissue culture techniques. Some trees have been regenerated from cell or tissue culture. The advantages of new varieties may be faster growth, improved fiber quality, greater disease resistance, and growth under adverse physical conditions.

The research on biotechnology in forestry is being conducted mainly in government and university laboratories, along with some farsighted, forest-based companies. It will take a long time to assess success in this area, but because of the importance of the forestry industry to countries like the United States and Canada, such research must be more aggressively pursued.

Pollution Control

The economic incentive for pollution control is probably not great. This conclusion suggests that national governments and international agencies may have to be the major developers of biotechnology for pollution control. Many opportunities exist. Historically, the first living organism to be patented as a composition of matter was an organism that had been given the capabilities to digest oil spills. Although the work on this orgarism was done in a major corporation, it was never commercialized. Since it is possible to discover or select microorganisms to metabolize almost any organic molecule, it is reasonable to suppose that detoxification of almost any toxic chemical could be achieved through biotechnology. Thus, such substances as dioxin could be converted to nontoxic materials.

Biotechnology may provide organisms to enable bioleaching and extraction of heavy metal contaminants. Coal, oil, and gas with high sulfur content may be desulfurized with microorganisms. Microorganisms may also be designed to enable toxicological monitoring.

Improved organisms for sewage sludge digestion may be developed. There is clearly a need in this area, but the industrial activity is small.

Mining and Metals Recovery

Biotechnology could affect mining in several areas. Microorganisms might be designed to improve leaching of minerals from low-yield areas. Such microorganisms used in the past were selected from those naturally available. Other microorganisms may be designed to recover phosphorus and manganese from the sea and to recover valuable metal salts from dilute aqueous solutions. Specific examples for biotechnology in this area are difficult to identify at this time.

Bioelectronics and Information

The more adventuresome futurists in biotechnology are beginning to explore opportunities for biotechnology in the area of bioelectronics. Some suggest that the ability to store large amounts of information by using the fundamental structure of genes and proteins will produce biochips—chips with greatly enhanced storage capabilities. There is a divergence of opinion among scientists as to the potential reality of biochips. Cells or products of cells produced by biotechnology may be used as biosensors in a variety of health care, industrial, and military applications. Biotechnology may provide the equivalent of biobatteries and may even lead to visual prostheses. Based on the above industrial sector forecasts, it is reasonable to conclude that biotechnology will have major impacts on most industrial sectors. In the next section, biotechnology-related issues will be discussed.

ISSUES

Biotechnology has generated and will generate an unusually broad set of issues, including safety, research policy, competitiveness of U.S. industry, ethical considerations, preservation of the genetic base, and security, among others. Some have been noted above. In this section, they will be addressed in somewhat greater depth.

Safety

Safety of laboratory workers was the first major concern associated with the initial work in the new biotechnology in the early to mid-

1970s. The concern about worker safety has expanded from the laboratory to the areas of manufacturing and job and product safety and has been joined by concerns about the impact of release of genetically engineered organisms into the environment. The NIH Recombinant Advisory Committee and the Recombinant DNA Guidelines have guided in a safe manner the laboratory and early scaleup activities.

Uniform domestic and international biohazards for laboratory scaleup and manufacturing work are desirable. The Recombinant DNA Guidelines have, to a significant extent, functioned in this manner by being viewed as the standard by a large part of the world. The Committee on Genetic Experimentation, created by the International Council of Scientific Unions, helped facilitate some uniformity across countries in safety for laboratory experimentation. Realistic international standards and agreements on uniform testing and certification of the products of biotechnology would also be desirable.

In the United States, products of biotechnology will be subjected to regulation by the Food and Drug Administration (FDA), the Department of Agriculture (USDA), or the Environmental Protection Agency (EPA), depending on the nature of the product. Jurisdictional questions must be resolved to avoid multiple regulation. EPA has indicated that those biotechnology products that do not fall under other laws will be regulated under the Toxic Substances Control Act, and EPA is moving to implement this position based on its interpretation that recombinant DNA and organisms containing recombinant DNA are potentially toxic substances. In such toxicity considerations, a reasonable approach might be to consider the toxicity of the products of the parent DNA or parent organism and then to evaluate the increase or decrease in toxicity of products created by the known genetic change.

The proposed release of genetically engineered organisms into the environment is producing major debate and, unfortunately, legal confrontations. Release must occur if any of the product opportunities in such areas as agriculture, forestry, mining, and pollution control are to be realized. A careful, stepwise progression from the laboratory through contained-growth rooms and greenhouses to limited field trials should provide adequate safeguards. In most cases, bactericidal, fungicidal, or herbicidal chemicals could be used to destroy the released organisms if unexpected risks occurred. However, in most cases a novel organism introduced into a new environment will need assistance to be able to compete, and without this assistance it will not survive. In addition, it is important to recall that no significant safety risk has been found for the new biotechnology, despite extensive examination. Requirements should be consistent with real risk.

Research Policy

It is critical to maintain and strengthen research policies that are consistent with developing a strong new biotechnology industry, as well as establishing ways to develop those products that are not attractive to the private sector. Federal funding of R&D must be maintained and expanded in selected areas to ensure our continued international leadership role. This includes the areas of health science, but also the areas of agriculture and some of the other sciences where our knowledge base is less adequate. Federal funding to assist training is also critical, since a developing biotechnology industry will need a growing number of trained professionals for R&D and marketing of products.

Additional government funding is needed in the United States for training in specific skills. The greatest deficiency is probably in the area of biochemical engineering, the hybrid of chemical engineering and molecular biology. Only a few academic institutions—less than 10—have programs to train these needed individuals. Most biotechnology products will require substantial process engineering, the domain of the biochemical engineer. The National Science Foundation provides only $1–$3 million of support in this critical area. This support should be expanded.

Some products of biotechnology will be economically unattractive to the private sector. These may include products for the disposal of hazardous wastes, orphan health care products, and specialty crops. These areas where the economic incentive is uncertain or poor for the private sector should receive federal support not only to provide the science but also to convert that science to useful products and processes. Subsidization of the private sector may be an alternate way to assure development of these needed products of low economic incentive.

Biotechnology is interdisciplinary. Funding can be used to promote this and to train interdisciplinarians. For example, government funding could promote a balance of interdisciplinary, multiple-investigator grants and the more common monodisciplinary, single-investigator grants. Most students are trained in the latter environment and find it difficult to adapt to the interdisciplinary nature of industrial biotechnology R&D. Cooperation of government, industry, and academe must be promoted with the objective that each segment be excellent in its respective role.

Priorities must be established for U.S. and world research. These priorities should include our national needs as well as those of developing countries. The major part of our biotechnology R&D will focus on national opportunities; some will focus on the needs of developing countries as part of our role in world leadership and development. We must also consider the impact that biotechnology may have on the competitive positions of some of our established primary industries, like production agriculture, where it has been hypothesized above that our competitive edge in the long term may be substantially decreased. If this hypothesis is true, we must identify other products that can be grown on our agricultural land and that will have as high a value in use as possible. R&D must then provide a base for enabling such crops to be produced and converted to useful products.

Although biotechnology may in the longer term decrease the competitive advantage of our agricultural primary production industry, biotechnology should provide major opportunities for our agricultural input industries to provide such products as seeds to the growing world market.

It is important that research policy recognize an important obligation of research to inform society about major new advances. This is especially true in biotechnology. Society will expect to have a vote in establishing the line between acceptable and unacceptable approaches. Human gene modification or therapy is a current example where the dialogue should have begun already.

Competitiveness of U.S. Industry

A major current concern of governments in most developed countries is to establish a strong, competitive biotechnology industry. Some of the various actions, such as government investment, have been discussed. In this industry, as probably in most others, the major factors that determine competitiveness are domestic, and the minor factors are foreign. One might suggest a division of 80 percent domestic and 20 percent foreign. Factors that influence competitiveness, such as a strong science base and training, proprietariness, regulation, site of manufacture, and export of products versus technology, will be discussed.

Science Base and Training

It is critical that the U.S. government continue to fund fundamental science to underpin biotechnology. The current leadership position of the United States in biotechnology exists mainly because of the liberal funding of health science research in the 1950s, 1960s, and 1970s. Although it is important for this to continue in the health science area, it may be of even greater importance to expand that funding to other science areas that will underpin biotechnology developments. These other areas include agriculture, forestry, food, energy, and pollution control.

Access to genetic material must be as open and free as possible so that time is not wasted in repeating already completed steps. It is unfortunate that universities whose funding for the most part comes from the public via government are not freely distributing the genetic materials created in their laboratories. The movement of genetic material from country to country may be a problem in the future. In the past, genetic material that naturally evolved in one country was collected and freely made available to other countries for use in breeding programs. For example, the major source of genetic material for U.S. soybean breeding has been China. Resistance to rust, which could be problematic in U.S. soybeans, has been found to occur in a soybean growing naturally in Australia. New, not naturally evolved, genetic materials are being constructed in developed countries. How freely should developed countries share these new genetic constructions with other countries? If we are restrictive in the distribution of the new genetic constructions, we may be restricted in the collection of naturally evolved genetic materials.

To facilitate the development of new biotechnology products, processes, and services, the basic information must be made readily available. The generators of basic scientific information must be encouraged to share that information. U.S. academic institutions, in their aggressive search for additional funding, have become increasingly entrepreneurial. This trend may generate some additional income in the short term, but in the long term it could undermine the strength of U.S. biotechnology and other industries.

Tax incentives may also increase industrial R&D activities, although the effectiveness of this approach has been questioned recently. For example, R&D limited partnerships have been used by some, mainly smaller or start-up, companies to obtain funds to support research. In other areas, limited R&D partnerships are being used to obtain funds to support clinical trials.

Proprietariness

Adequate proprietariness will, in the long term, be key to the development of a successful and profitable biotechnology industry. There are several unanswered questions regarding proprietariness in the biotechnology area. Although the Supreme Court indicated a few years ago that living organisms, such as a bacteria, with new capabilities can be patented as new compositions, it is not clear what range of living organisms may be patented. Will animals, such as the superrodents, be patentable? Are sexually propagated seeds covered by the Patent Act? There may be some confusion in this area because there is also the Plant Variety Protection Act, administered by USDA, which provides a certificate, not a patent, for new, definable, sexually propagated cultivars, although vegetatively propagated cultivars are covered by the Patent Act.

Many of the early products of the new biotechnology will be proteins, since genetic engineering produces proteins as the direct products of genes. Natural products have not been patentable as new compositions of matter. It would be desirable to extend the patent law to include natural products, such as proteins, when their composition is first described. Similar abilities to patent natural products other than proteins would also be useful to facilitate commercial development of these molecules.

Most therapeutic or agrochemical products require extensive testing to demonstrate both their efficacy and safety prior to obtaining governmental permission to market in the United States and many other countries. The governmental agencies include FDA for food and drugs and EPA for agrochemicals. Premarketing clearances require 5–8 years, which consumes part of the useful patent life of 17 years. In recent years, congressional efforts have been made to restore patent life so that a period equivalent to that lost for regulatory clearance is added to the life of the patent. Since many of the products of the new biotechnology will also require equivalent regulatory clearances, patent restoration is equally critical to this area.

The above comments are directed at the domestic scene. The competitive position of U.S. industry would be improved if there were international conventions to provide greater uniformity with respect to patentability and proprietariness. Some countries do not recognize proprietariness, and this will significantly retard the development and early commercialization of products that would improve the health and food supply of these countries. Unfortunately, those countries that in many cases do not recognize proprietariness have the most pressing health and food problems.

Regulation

Many of the products of biotechnology will require registration prior to marketing in the United States and in most other countries. Because of our limited experience in the use of biotechnology products (for example, therapeutics), it is logical that the regulatory requirements for these products be equivalent to those established for synthetic chemical products. If these products of biotechnology that mimic those of naturally occurring body chemicals have no major problems, it would be appropriate to establish a less demanding and more rapid federal procedure for their approval. This statement is based on the recognition that many of these products are natural products and therefore are formed and exist in humans and are probably generally less toxic than synthetic foreign chemicals.

Problems exist in the international regulatory area as they do in the proprietary area. Currently, data that show safety often must be generated in each country for which approval is sought. It would be more economical and rapid to have reciprocity so that appropriate safety data would be accepted by most countries. It is difficult to see how animal safety data for an agrochemical will vary according to the country in which the experiments are done. The problems of products of biotechnology in this respect are similar to those of current agrochemicals and therapeutics.

Site of Manufacture

Some countries require manufacture in the country of use. Such requirements may increase the cost of many biotechnology products, since the high potency of the products will require the manufacture of only small quantities. A single manufacturing site would be much more economical than multiple sites. Furthermore, the number of jobs provided by manufacturing biotechnology products will not be as great as the employment historically provided by the smokestack industries. Also, a requirement of within-country manufacture will probably delay the delivery of some biotechnology products to some countries.

Multiple, small manufacturing facilities within many countries may be operated in a less safe manner. Some companies are establishing non-U.S. sites of manufacturing possibly because of the concerns regarding unreasonable U.S. safety requirements.

Currently, most unregistered materials that are manufactured in the United States cannot be exported, even if the recipient country will allow them to be used. It may be desirable to enable the export of such materials to encourage manufacturing in the United States, with its attendant generation of additional employment and favorable trade.

Another loophole makes U.S. companies with process patents vulnerable to foreign competition. A foreign company may use a U.S.-patented process to manufacture a product and sell it in the United States in direct competition with the U.S. company owning the patent. Legislation is needed to cover these product-by-process cases. Such cases are to be expected for biotechnology processes, as they are for other processes.

Export of Products Versus Export of Technology

The United States currently has a leading position in the commercialization of biotechnology. This is in major part due to the large number of start-up companies that are aggressively seeking to convert the technology to products, processes, and services. Already, some of these start-up companies are selling their technology to foreign countries to obtain needed funds for developing their products in the United States. Such actions may be appropriate and critical to the start-up companies but may not be appropriate to the national interests of the United States, since it can be argued that potential jobs and profits in the manufacture and marketing of the products based on this technology are being exported by licensing. Should policy be developed to enable government to meet the funding needs of the start-up companies so as to avoid export of the technology?

Ethical Considerations

The new biotechnologies are and will continue to be the center of much ethical concern. Some of this stems from an inadequate understanding of genetic engineering by a large part of the population, some is due to anxiety associated with the unfamiliar, some is due to a suspicion of science generated by the nuclear era, and some is due to a belief that genetic engineering is tampering in an area that is not meant to be changed by humans. Some ethical concern is due to a highly vocal segment of society whose philosophy is inconsistent with commercial endeavors, even though these efforts have a high potential for delivering improved products for health care and food production. For example, how can one oppose such biotechnology-derived products as growth hormone, which enables children destined to be dwarfs to become normal adults? It is imperative that we expand our efforts to educate today's students in the positive and negative realities of the new biotechnology so that they will be able to make informed decisions.

Biotechnology will create many new products and processes that will, in general, be expensive. Expensive and speculative R&D will be entailed in generating these products and processes. We must consider how such a much expanded arsenal of costly health care products will be made available to the economically deprived in the United States and elsewhere in the world. What is our obligation? What can we afford? How will we do it?

We must anticipate the improved longevity and resultant expanding population that will result from removing or reducing in a major way key present-day killers in the developed world, such as cancer or cardiovascular disease, or, in the longer term, from the delay of aging. What will be the impact of this expanded and older population on various social arenas, such as the workplace, recreation, retirement, and the amount and kind of food desired? As noted below, the health impact of biotechnology may precede the agricultural input in the less developed countries, producing a worsening of the food-to-people ratio in the intermediate term, suggested to be the early twenty-first century.

Like developed countries, Third World countries have high expectations for biotechnology to improve their health, food supply, and economies. We need to plan how to develop biotechnologies whose products and processes will be focused on needs of developing countries—needs that, for the most part, will differ from those for developed countries. To do so will entail a major transfer of skilled people or the training of citizens of developing countries or both to establish biotechnology programs in these countries. In the long term, biotechnology may have more impact on the quality of life of developing countries than on that of developed countries and may be the major equalizing input of the next century. The early agricultural successes of the Rockefeller Foundation plant-breeding programs with wheat and rice provide models, but the new biotechnology requires skills more complex than those used in plant breeding. Alternatively, industry may be encouraged through low-interest loans to introduce biotechnology products into the developing world.

Eventually, somatic cells from an individual may be used to generate complete organs and maybe, in time, complete organisms. We need to discuss what is permissible and what is not permissible to society in the use of such capabilities with human cells.

Preservation of the Genetic Base

Many believe that it is important to conserve the broad diversity of naturally evolved genetic material that now exists in nature. Modern agriculture tends to minimize genetic diversity, since it uses a few genome types broadly throughout animal or crop agriculture and thereby eliminates most of the naturally occurring diversity. The new biotechnology may provide means to store DNA or to store the information of DNA so that it can be regenerated for some future use. Also, capabilities to design genes that have not yet existed in nature are being developed. Such capabilities may in time free us from the need to be concerned about maintaining all of the present diversity of genetic materials. We must decide how to preserve the genetic base and to what extent it is possible and desirable to do so.

Security

In terms of security, it is possible to envision the use of biotechnology in both offensive and defensive contexts. In an offensive context, a recent U.S. Department of Defense report suggests that the Soviet Union may be trying to apply biotechnology to a broad biological warfare research effort. The expanding knowledge of human, crop, and animal diseases at the molecular level and the ability to counteract specific diseases may make it possible to subject a major land area to a decimating, biotechnologically designed disease to which crops, animals, or people of the inflicting nation would be resistant because of biotechnologically designed vaccines or equivalents. One might imagine the use of a lethal modification of a common disease with high infectivity, such as the common cold or influenza viruses. Biotechnology in warfare today may be viewed as a more technologically sophisticated biological warfare than that of a few decades ago. It is hoped that civilized people will not pursue this route. (They earlier agreed to stop biological warfare research under the Biological and Toxin Weapons Convention of 1972.)

The U.S. military also has biotechnology research of a defensive nature under the Defense Advanced Research Projects Agency. It has been reported that most of this effort is to develop vaccines for existing international diseases, such as rickettsial diseases, and to develop ultrasensors to detect toxic substances in the environment. Thus, biotechnology may generate products to protect against disease or toxic agents and to monitor in a highly specific and sensitive way health and environmental threats.

Concerns about security in the biotechnology area may result in export controls. Decisions regarding such controls will require informed inputs so as to limit the export of any real security risks, but not that of non-security-risk products. The real security risks from biotechnology will probably be very few.

Biotechnology and International Relations

Biotechnology has some significant, unique issues and some that are common with other technologies. It is fortunate that the new biotechnology is very early in its evolution, and some time is available to establish policy rather than to react to crisis situations.

A decision must be made on the U.S. role in biotechnology for the developing countries where this technology may have substantial impact in the long term. How will the necessary skills be provided? How much should we emphasize research whose outcome may have little positive direct benefit to the United States and may even decrease the competitive advantage of U.S. primary industries? An example is the development of a vaccine for foot-and-mouth disease, a disease that is insignificant in the United States.

Biotechnology may produce an imbalance in the people-to-food ratio in the intermediate term. This hypothesis is based on a more immediate impact of biotechnology in health care than in food production. Ultimately, health care and agricultural biotechnology may lead to a much larger population, with the resultant negative impact that a dense population has on quality of life. How can we use the benefits of food and health biotechnologies and the increase in longevity while avoiding a population explosion?

Security issues are important in the biotechnology area, since the offensive use of biotechnology for warfare purposes could be disastrous. Honoring existing agreements would limit or preclude such activities.

Several of the aforementioned factors will be key to a strong competitive position in world biotechnology. At the same time, being viewed as a leader in biotechnology is essential for maintaining a world leadership position. We must establish policies for biotechnology-related issues so as to obtain maximum benefits in both the national and the international spheres.

SUMMARY

The new biotechnologies are fundamental and pervasive techniques that are expected to affect many industries broadly. Although there is no biotechnology industry, there is a potential major biotechnology subset of many industries. These new biotechnologies are in their most early log growth phase and thus have negligible current sales, but a huge sales potential is expected at maturity in the twenty-first century. The United States is clearly the world leader, with developing competition in Japan and Western Europe. There are many challenging issues to assuring a competitive U.S. position in biotechnology and to dealing with a large number of ethical considerations in which society will expect to have input.

Some of the more significant international relations issues include:

- Security (defense, offense, and export control)
- World population (people/food ratio and quality of life)
- Biotechnology for developing countries (needs, skills, and financing)
- Importance to world leadership position
- Competitive position (research policy, science base and training, proprietariness, product versus technology export, regulation, trade policy, and primary producer versus input industries)

One significant possibility is the concept of biotechnology in the longer term as a force for decreasing the difference, at least in primary production industries, between developed and less developed countries. A specific example may be a marked decrease in the competitive advantage of U.S. crop and animal production agriculture. We must plan to provide options that minimize the negative impacts of such significant changes.

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International Relations in a Technologically Advanced Future

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NEWSPAPER HEADLINES RECORD the fact of political and economic disputes between advanced industrialized countries, whether the issue is trade protectionism or the suitability of building an oil pipeline to the Soviet bloc. What is less well documented and understood is the role that technological innovation plays in creating or aggravating those political and economic disputes and the role that technical change can play in resolving those disputes. The aim of this paper is to suggest various impacts that technological change—particularly in the six areas of technology forecasted elsewhere in this volume—will have on relations between advanced industrial states.

The view ahead will be over the next 10–15 years—that is, we will concentrate on the problems that advanced industrial nations will face by the mid-1990s. Given this time frame, however, we must entertain some flexibility about which countries can be considered "advanced" or "industrialized." The present group of 24 nations that are members of the Paris-based Organization for Economic Cooperation and Development (OECD) may no longer comprise all of the developed countries. Current and future rates of growth, particularly among certain Asian countries, may bring Korea, Taiwan, and Singapore into the ranks of advanced societies. Other newly industralizing countries may resume earlier rates of growth. Brazil, for example, may be counted among the industralized societies if it can recover from its current debt problems. And in the Middle East, major oil producers are investing heavily in education, training, and a modern industrial base that may transform these countries into industrial states.

This expanded group of advanced societies will have a special relationship to technological change. Although the less developed countries will benefit significantly from new productivity-enhancing technologies, it is the developed countries that will generate and absorb the preponderance of the new technologies. Indeed, the developed countries can be characterized as having a high productivity in generating new technology. Investment in education and in research and development (R&D) are part of a pattern of receptivity to change. The rate and volume of technological change will have a major impact on economic, social, and political life in these societies as well as on relations between these countries.

Before examining the specific technological changes that can be anticipated and their consequences for the advanced states, it is useful to set out our understanding of technological change in a broad historical context. In our view, technological change is an integral part of the social and economic systems of advanced societies. The systematic application of human and financial resources toward the development of useful knowledge, the basis for technical change, has been present for nearly 200 years. Indeed, what distinguishes the past century from earlier periods in human history is that Western societies have institutionalized the process of technical change. This institutionalization has occurred mainly in our universities and major businesses, often with some support from government. Individuals still play a key role in generating profitable new ideas in our societies. Residents of advanced nations have come to accept technical change as a basic fact of life.

The institutionalization of technical innovation has produced steady technical change that has augmented the productivity of the labor force at a rate of about 2 percent a year over the past century. Higher standards of living have been one result; structural change in the character of economic activity has been another. New industries have come into being while others have declined or even disappeared.

In light of this history, we accept as our baseline the trajectory of change, rather than the status of, say, 1984. This significantly influences the questions that we will ask about the future. A relevant question in this framework is whether the change that we can expect over the next 10–15 years is likely to be qualitatively different from that of the past 10, 20, or even 50 years. Will the process be different or will it be like that we have seen in the past? And, if it is the latter, will its impact on foreign relations be similar to what we have observed in the past?

To put our view in overly simple terms, we have chosen to emphasize continuity rather than change—but it is a continuity that assumes that change is steady and ongoing. The changes that we expect over the next 10–15 years will be qualitatively similar to those that have occurred since World War II, and the impact on relations between industrialized countries will, by and large, represent a continuation of trends long under way. These trends will continue to "shrink" the world, to reduce the autonomy of governments, and to increase the permeability of societies.

In the future as in the past, efforts to block, resist, or channel these impacts will also be with us. We have seen governments act to control the transborder flow of data and information, to protect declining industries, and to promote leading competitive industries. As competition from new countries and new industries increases, government efforts to mitigate the resulting social dislocation will continue. The net impact of new technological forces confronted by government policies of resistance will nonetheless be toward reducing the freedom of national governments to manage their societies. Increased proximity, permeability, and interdependence will be the trend of the future.

In the following pages, we address four aspects of technological change among the developed societies. The next section reviews the technological changes that have been forecasted in the following six sectors: energy, new materials, computers, telecommunications, aerospace and aviation, and biogenetic engineering. The following sections consider the social, economic, and political impacts of these changes for advanced industrial societies and the impact of these trends on the capacity of national governments to satisfy the growing expectations of their publics. A final section draws some implications of the trends and of the impact on governments for international relations—both conflict and cooperation—between advanced countries.*

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*In writing this paper, we have drawn heavily on the technological papers published elsewhere in this volume. Therefore, we have not footnoted sources to the technological projections. Readers interested in more detail should refer to those papers.

KEY TECHNOLOGICAL DEVELOPMENTS

General trends in technological change can be forecasted for energy, new materials, computers, telecommunications, aerospace and aviation, and biotechnology over the next 10–15 years. What cannot be predicted, of course, are major unexpected breakthroughs or disturbances to the system. But current developments in the R&D "pipeline" suggest that over the period in question, a continuation of past technological trends, rather than radical new developments, will have the main influence on relations between the developed states. By 1995 significant changes may be on the horizon that will affect those relations more radically in the twenty-first century.

An additional source of uncertainty in anticipating the impact of new technology is the rate at which new technological options will be actively assimilated. The mere generation of new technological possibilities will be less significant than their absorption into existing systems of production, distribution, and communication. Adoption will be influenced by such factors as government policies and the rate of economic growth.

Energy

Of the six sectors to be considered, that of energy is perhaps the most difficult to forecast in some ways, and yet easiest in others. Over the past 10 years there have been no major innovations in energy technologies. There has, however, been a steady pace of technological improvement, not only in energy utilization and conservation but also in production. The pace of technological adaption has very much depended on the price of oil. The impetus for commercialization of synthetic fuels and for enhanced techniques for tertiary recovery of oil has come from the rapid escalation of oil prices in the 1970s. Although technological improvements will continue, major breakthroughs are unlikely. Given the large capital requirements and long lifetimes of existing energy facilities and the time it takes for a new energy source to capture a significant share of the market, major transformations in the world energy picture are probably 50 years away, at least. Rather, a gradual shift in relative importance of different energy sources is likely.

Thus, in one respect there is a high degree of predictability to the future sources of energy for modern industrial systems. Oil's role will decline, but oil will remain the leading energy fuel, still providing more than 40 percent of total consumption by the year 2000. Gas will retain roughly its present share (a bit over 10 percent) of total energy use. Coal use is expected to increase from its current share of 21 percent to 30 percent. Nuclear power may be the single most rapidly growing source of energy, especially in Europe and Japan. However, it is unlikely to provide more than 10–11 percent of energy for the OECD nations in the year 2000. Other sources of energy in the same year, including hydropower, solar, and biomass, could account for 10 percent of projected energy output.

This outlook is based on a number of plausible assumptions about economic growth, the price of oil, and improvements in energy conservation and efficiency. It is at this point that significant elements of unpredictability enter the picture, making it hazardous to rely on these forecasts. History has demonstrated the unreliability of predictions about the availability and price of oil in the face of political and economic disruptions. Although the market can and does adjust to disruptions, the process affects the rate at which innovation occurs and is adopted by other energy sectors as well as by all other sectors of the economy and society. Assumptions about the pace of economic growth may be wrong. There may be major oil supply disruptions as a result of war or political turmoil in the Persian Gulf. This possibility is sufficiently likely that it must be given serious attention in foreign relations between industrial countries. If such events lead to significant changes in oil prices, other fuels may be substituted for oil at a more rapid rate. Also, price-sensitive improvements in energy conservation and efficiency could reduce world oil demand by somewhat more than the above projections imply.

Government actions and policies will also determine the direction and pace of technological change. The United States is facing critical decisions about continued support for R&D on synthetic fuels. Government decisions on the licensing of nuclear reactors will affect the future course of nuclear power in the United States. France and Japan, meanwhile, are investing heavily in nuclear energy, which will keep that technology moving ahead.

Within broad outlines, the energy forecasts assume a steady state of technological change in all energy areas. In the absence of any major breakthroughs, relative dependence on oil will decline, but oil will continue to dominate the energy scene while other fuels gradually increase their share of total energy supplies. The price of oil will be critical not only to other energy sectors but also to developments in other major technology areas.

New Materials

The pace of technological developments in the materials sector has been advancing rapidly and can be expected to continue through the remainder of this century. The advances of the future will build directly on those of the past. The changes that can be expected include new combinations of materials and the development of alloys or materials with improved properties. The key point is an improved ability to design materials to meet desired performance requirements, rather than just to adopt the best material that nature provides. Among the new characteristics being sought are special magnetic properties and higher strength and stiffness relative to density. A variety of multifunctional composite materials can be foreseen. High-efficiency, electroluminiscent materials as well as chemically sensitive electronic devices are to be expected. Structures with layers only a few atoms thick will offer new properties. Interpenetrating material structures offer promise for new electric and magnetic properties. Polymers will continue to improve, as in the case of new polymers that will more efficiently conduct electrical and optical signals. Electronically active polymers may be combined with graphites for improved conductivities. Ceramics will also continue to improve since they can be made crack resistant, allowing the development of higher-efficiency and lower-energy-consuming engines and turbines.

Improved materials processing or fabrication offers equally exciting prospects for techniques that reduce total manufacturing costs and enhance performance of the processed material. Advances in fabrication techniques may reduce the extent of final machining or grinding operations on forge products. Further advances in compaction of ceramic and metal powders, as well as microjoining and diffusion bonding, are in the offing. Rapid solidification, high-pressure synthesis, and hot isostatic pressing are other techniques that will improve the properties of metals and alloys.

The patterns of industrial and commercial use will interact with and affect the pace of these technological developments, the materials that will be selected, and the way they will be processed and fabricated. In the development of materials related to energy production and use, for example, we will continue to see efforts to develop lighter and stronger materials to reduce friction, wear, and overall energy use in transportation. There will be improvements in the durability of ceramics to allow their use in more efficient high-temperature automotive or other engines. High energy costs will promote an emphasis on processing techniques that save energy. Changing patterns of use can lead to a trend away from traditional materials and toward more exotic materials, or, as techniques are developed to enhance the properties of traditional materials, the trends may be toward greater use of improved but traditional materials. Relative costs of new and traditional materials will be an important factor in the pace and direction of technological innovation in new materials.

Computers

Increases in the capabilities of computers have followed a steady trend since 1945, even though there have been radical changes in technology. After the integrated circuit was introduced in 1958, the number of transistors that could be placed on a single chip doubled every year until the 1980s, when the rate slowed to a doubling every 1.5–2 years. Similarly, computer memories have undergone significant changes over the past 40 years, evolving from vacuum tube computers, storing one digit per tube, to bipolar and metal oxide semiconductor integrated circuits. The capacity of the dynamic random-access memory chip has improved enormously over the past decade, with the 1 million-bit chips likely to be available in the next few years.

The evolution of computer technology has gone through three stages. The first, beginning in the 1940s, was the engineering effort to build computers to do complex calculations. The second, beginning in the 1960s, focused on improving machine productivity. The third stage, which will be with us for some years, involves improving productivity of the human inputs. The constraints on future computer developments include software, the rapid expansion of data, and the availability of technical skills. The goal in the years ahead is to "educate" the computer to move beyond skilled users to handle voice communications.

Specific developments and technological changes can be anticipated in the coming decade. Techniques for using memory efficiently and structuring databases to achieve rapid responses will be important. Computer architectures will be developed to support several programming languages that are more responsive to the specific needs of software. The variety of peripheral devices will expand to meet specialized user needs. Improved local area networks will allow different terminals, computers, and peripheral devices to communicate with one another. Machines that adapt to the user can be expected. There will be a revolution in the techniques for producing and using software. Advances in educating the computer to solve more complex problems will continue.

The most dramatic changes that lie ahead are in the widespread use of the "user friendly" personal computer and in the incorporation of computers in a wide range of household and business equipment. Manufacturing processes are already being revolutionized by computer-aided design and manufacturing based on quick, highly accurate feedback control.

Although engineering developments will continue to promote a steady growth in performance, limits on certain technologies are in sight. We may, for example, be approaching the limits of silicon technology for miniaturization. It is possible, however, to predict the availability of 64-megabit memory chips before the turn of the century (chips storing up to 256,000 bits are just coming into use now), although the particular technological breakthroughs needed to develop these chips cannot be easily forecasted. Important changes, however, will be in the development of easy-to-use computers, the incorporation of microcomputers into a wide range of factory, office, and household equipment, and the continuing dramatic decline in computational costs.

Telecommunications

Dramatic technological change has characterized the telecommunications industry since the 1940s. There have been significant increases in the number of voice circuits that wire, cable, and radio relay systems have been able to carry. A radio channel that originally carried 480 voice circuits can carry 6,000 today. The latest coaxial cable system can carry more than 132,000 calls on a single cable. With the increases in the carrying capacity of voice circuits has come a major reduction in cost. The Bell System's long-haul transmission network cost $158 per circuit mile in 1940 for 2.8 million miles. In 1980 the cost of 510 million circuit miles was $11 per circuit mile.

The "information age" that lies ahead anticipates continued trends in technological improvement, extended services, and cost reductions. Two areas of technological change—microelectronics and software—have been considered in the computer area. Exponential growth in the number of components per chip and increases in speed have been mentioned. Speech processing that will allow automated voice dialing or automatic translation of conversation or written speech into another language is a major threshold to be crossed.

The third and fourth areas of technological innovation are optical and satellite communications. The advantages of lightwave communications systems are their large information-handling capacities, their immunity to electrical and electromagnetic interference, and their low signal loss. Substantial progress is expected in transmitting higher ratios of information per fiber and increasing the spacing between repeaters. Optical communications also offer the promise of moving from the voice band to video-bandwidth channels.

Although communications satellites will not have as extensive an impact on telecommunications as microelectronics, software, and optical devices will, they may be expected to increase their utility by developing higher-frequency bands and narrow-beam, directional scanning coverage patterns. In the telecommunications area, their primary advantages will continue to be that they permit rapid initiation of services, point-to-point transmission over difficult terrain, and transmission of data to many locations simultaneously.

Aviation and Aerospace

Developments in space and aviation will continue to be affected by cost reductions brought about by trends in energy efficiency, developments of new materials, and advances in computer technology. During the past decade, operating costs of air travel per load mile have dropped 43 percent. Over 30 years of experience with commercial jets has seen a demonstrated improvement of 30 percent per decade in fuel efficiency. Despite these improvements and recent declines in the price of energy, fuel still accounts for over 53 percent of direct operating costs. Further improvements in fuel efficiency are therefore critical for future aviation costs.

Technological innovation that will enhance efficiency and reduce costs involves changes in materials, control systems, avionics, electronics, and power plants. Improvements in materials to reduce the weight of the airframe while maintaining strength are on the horizon. The substitution of electronic control systems for hydraulic and mechanical control systems will also bring substantial weight savings. The use of digital electronics systems to design and test aviation systems will offer a powerful development tool. Improved design features will allow for increased loads. Although efficiency of current jet engines is expected to improve through improvements in materials and design, progress toward highly efficient turboprops or other forms of propellerlike engines is also likely.

The integration of all of these technological advances offers the promise of increased efficiency in the design and functioning of aircraft. Improvements in computers and telecommunications will make it possible to improve air control systems and thereby reduce transport costs arising from weather uncertainty, bottlenecks at airports, and other sources. Spacecraft will also improve, and exciting new knowledge will be acquired from space exploration.

Biotechnology

Among the six sectors considered here, biogenetic engineering is the most likely to experience technological breakthroughs by the mid-1990s. There are two major new biotechnologies at present. Genetic engineering makes possible a direct molecular manipulation of genetic material by isolating a gene from all other genes and then by placing it into a host cell so that it can function and be reproduced. The second major new biotechnology—the use of hybridomas* in the production of monoclonal antibodies—allows the culture of plant or animal cells and tissues to regenerate the whole organism from a single cell.

Additional biotechnologies to be developed over the coming years will evolve from such fields as embryology, immunology, and neurosciences. The areas of application receiving the greatest attention currently and having the most promise over the decade ahead are health care and agriculture. Products of biotechnology for health care include new vaccines, therapeutics, diagnostics, delivery systems, transplants, and gene therapy. Animal agriculture will be affected by vaccines and diagnostics. Crop agriculture will develop more effective microorganismal soil inoculants, plant testing, genetically engineered seeds, and biocontrol agents for insects, diseases, and weeds.

Other areas that are being investigated, but with less emphasis, are food and food additives, industrial chemicals, forestry, pollution control, mining and secondary metal recovery from ores, and bioelectronics. The future scientific priority attached to these areas will be a function of commercial interest. By the mid-1990s, these areas could be areas of major promise, but they are unlikely to have had a major impact by that time.

*A hybrid cell produced by the fusion of an antibody-producing lymphocyte with a tumor cell and used to culture continuously a specific antibody of a single molecular species.

ECONOMIC, SOCIAL, AND POLITICAL IMPLICATIONS OF TECHNOLOGICAL DEVELOPMENTS

We will attempt to draw some implications from the technological trends identified in the previous section. This is inevitably a chancy exercise, since the technical possibility of doing something does not assure that it will happen. Actualization depends on receptivity, which in turn is strongly influenced by social mores and by the economic feasibility of the new technique compared to that of existing practice or of other new alternatives. Even political factors can influence the adoption of a new technical possibility, as when government financial support or regulatory approval is required (e.g., nuclear energy or genetic engineering), so the extrapolations we make here must be viewed as likelihoods rather than certainties. We identify ten important developments:

1. Energy use in all industrial countries has dramatically decreased since 1974 relative to total production in those economies. The reduction has occurred in all sectors, but it has been especially noticeable in manufacturing. We see this process continuing, since real energy prices, despite some decline in 1983, remain much higher than they were 15, or even 10, years ago and because it takes a long time for modern economies to adjust fully to a new level of energy prices. An assumption of cheap energy was engineered into the capital stock we have inherited. It takes 8 years to turn over stock in automobiles. Homes can be insulated after they are built, but only when they are replaced will they be made fully energy efficient in accordance with current levels of energy prices and technology. Commercial structures built on the assumption of cheap energy for heating or cooling often have a life of 40–50 years. So energy conservation will continue for many years as new investment occurs and old structures are replaced.

During this same period, however, economic growth will increase the demand for energy, especially in less developed countries. Most projections show an increase in demand for oil between now and the year 2000, despite the energy conservation noted above and despite considerable switching to other fuels, such as coal, nuclear power, and (in Europe) natural gas. The demand of non-Communist countries for oil is likely to be in the range of 60–70 million barrels a day by the year 2000, up from around 50 million barrels a day in the depression year of 1982 (but perhaps not up from the peak of 63 million barrels a day in

1979). In short, there will be a steady progress in limiting the increase in the demand for oil, but dramatic reductions are not likely to occur within our time horizon. It takes a long time to bring on line new systems of energy with substantial magnitude, 10–12 years for a single nuclear plant in the United States (6 years in Japan and Korea). Conversion to coal has been delayed by weakness in oil prices and availability of gas; the development of shale oil and coal liquefaction has been postponed for the same reason. As a consequence, our continuing vulnerability to a disruption in oil supplies will become apparent when the world oil market tightens again. This will represent a feature of the world economy and a concern for foreign policymakers in the 1990s.

Looking beyond this century, the relative importance of coal seems likely to grow for some time, with the United States being a major supplier and Japan and Europe being major buyers. This development will require cooperative financing of infrastructure, including novel ways of transporting coal to and from ocean ports (e.g., by pipeline, mixed with oil or water).

2. One of the important contributions of new materials will be toward conserving energy. They will do this partly by weight-reducing substitution for heavier materials, such as steel and copper, in moving vehicles, like autos, trucks, and airplanes, thereby reducing fuel requirements per ton of payload. They will also conserve energy partly in the production process, where less energy will often be needed to make a new substitute product to perform a specified task (e.g., laminated graphite fiber as a substitute for aluminum on the skin of an aircraft). Both factors will help reduce costs of transport, especially air transport (more on this below).

Depending on which new materials are developed, demand may be reduced for some of the traditional materials, such as steel, copper, and aluminum, putting strains on existing industries that already suffer from excess capacity in the world. In the near future, protectionist pressures in these sectors will especially affect new suppliers of steel or refined aluminum and copper, such as Brazil or the Philippines. In addition, the substitution of new materials for traditional metals will tend to depress earnings of ore producers around the world unless new uses are found. The effect on demand for the more exotic materials is difficult to judge. As tailored alloys replace standard metals, demand for the alloying components will rise. At the same time, we are finding new materials to substitute for the special properties of some of these alloying components. As a result, for example, dependence on cobalt may in the future be less absolute and more sensitive to the price of cobalt as compared with those of alternative materials. One implication of this development is that the U.S. strategic stockpile will have to be drastically revised by the mid-1990s if it is to remain useful, and perhaps it will have to be radically expanded in concept to encompass not only materials themselves but also the productive capacity to permit easy switching from one material to others that are close substitutes.

This shift away from some traditional materials does not ensure against materials scarcities of the types experienced in 1951 and 1973. Those periods of commodity scarcity were short-run in character and arose when demand (including speculative demand) rose sharply relative to the then available capacity to produce. Such periods of short-run scarcity can be expected from time to time in the future as well, and the only surprise will be the ever-present tendency of contemporaries to interpret such temporary shortages as permanent features of the future environment.

3. The most dramatic feature of the electronic revolution is the sharp decline in the costs of complex computations and of long-distance communication of information. Together with a continuing decline in the relative costs of transportation, these developments will eventually revolutionize the processes of production and distribution of goods and services, although this change will not be completed within our 10–15-year time horizon. For example, computational speed has risen from 34,000 arithmetic operations per second in 1961 to 800 million in 1981, and computational costs have dropped by 90 percent over each of the 2 decades. Communications satellite unit charges dropped by nearly 90 percent in real terms between 1965 and 1982. These trends, although dramatic, will continue, with a consequent increase in the demand for these services.

Computer-aided design along with reprogrammable robots will permit small, specialized production runs for many diverse products around common basic designs. Products can thus be made to order or made for inventory and replenished quickly as sales are made from inventory. Cheap and reliable transportation will permit products to be shipped from relatively few points of production to almost anywhere in the world. On both counts there could be a dramatic reduction in the need for inventories in the production-sales sequence, thus conserving capital. (Inventories, including unfinished materials, account for about 15 percent of the physical capital stock of the United States. Reducing this to 10 percent would represent a substantial savings of capital.) Moreover, consumers could be offered greater variety at costs in the past permitted only by mass production, and even specialized equipment could be produced at something close to mass production prices.

With heavy business reliance on long-distance communications for inventory control, design work, internal financial planning, and so on, there will be a heightened interest in business cryptography to keep information out of the hands of electronic eavesdroppers.

With low-cost, high-volume communications, the service industries will be transformed. Physical location of retail outlets for financial services and even goods will make much less difference than it does now. We can imagine electronic catalogs from which customers call up items on a home television screen, examine them, place their orders electronically, and receive the purchased product within a few days—from one of many places in the world. This would be true not merely for goods but also for services, such as insurance or brokerage services, financial counseling, or even medical advice. A forerunner of this development is the establishment of an all-electronics futures market in Bermuda, physically located far from traders and beyond the jurisdictional reach of the major countries.

4. The world will continue its trend toward becoming a "global village" as far as communications is concerned. The World Cup Match or a British royal wedding are already global events. The list will grow. We may see the emergence of international politicians—Anwar Sadat was a forerunner—pleading their causes directly to publics in many countries. It will be harder than ever for governments to separate their audiences, telling one thing to the domestic public and another to foreigners. The result will be less duplicity but more ambiguity in government positions on various issues. Once a position is taken, widespread publicity will make it difficult to change. Barriers of language will continue to permit some separation and inhibit the emergence of world political figures, but even that may be overcome with machine translation and interpretation, which is now being developed.

We are witnessing a trend from political representation to new forms of political participation. Candidates for office and national leaders are increasingly seeking direct and timely feedback on the policy preferences of their electorates. With this capability, the role of the constituency representatives or legislators may be reduced as executive authorities move into a position to read voter sentiment directly. Rather than turning to the congress of local leadership, they will seek direct feedback through polls and surveys. On an international scale, this phenomenon could be translated into the ability of national leaders in one country to get a direct reading on the political sentiments of the population in another country. This possibility could expand the opportunities for circumventing the national leadership and appealing directly to selected publics in other countries, thereby creating transnational constituencies on a scale larger than any we have seen. Israel's cultivation of American public sentiment is a forerunner of this practice.

Political groups will increasingly project their causes into the world scene via the electronic media with dramatic appeals of various kinds, including terrorist acts by radical and disaffected groups. Along with growing ease of communication and transportation, we will see increasing internationalization of crime and the use of foreign sanctuaries, but modern technology will also contribute to an ability to penetrate criminal syndicates and to detect criminal activities, as when major cocaine arrests in Colombia were made possible by satellite detection of radio communications between the various parts of the cocaine operation. Computerized fingerprint storage and analysis permits rapid identification even over long distances.

5. Improvements will continue in transportation, especially air transportation. Cost per ton-mile has declined dramatically over the past 30 years, and there is every reason to believe that the trend will continue as a result of the many possibilities for further improvements in aircraft efficiency. All-weather landing capacity can be installed on commercial aircraft, thus reducing expensive weather delays. As demand calls for it, aircraft can be enlarged beyond the scale of the Boeing 747. Short-takeoff aircraft are likely to become much more prevalent on relatively short intercity routes, facilitating the development of air transportation hubs.

Relative to other prices, the price of air transportation will continue to decline. Already, 20 percent of U.S. exports by value are shipped by air, as are 11 percent of U.S. imports. These shares will increase over time. With fast, reliable, relatively inexpensive transportation and with cheap and reliable long-distance communication, geographic location of plants close to the market becomes less important for many goods than it has been. Production can be concentrated at a convenient place (near an airport), and orders can be received and shipments can be made around the world. As noted above, such an arrangement would permit a significant drop in inventories relative to sales.

As to the use of space, we believe that it will not be significant in our

10–15-year frame beyond telecommunications and military uses. However, the widespread perception that space may be commercially important for manufacturing in the future, fed by El Dorado tales emanating from the National Aeronautics and Space Administration, will ensure heavy interest in space activities by major governments, thus providing a field for both conflict and cooperation.

6. Developments in biotechnology will improve further the yields of agricultural crops over the next 10–15 years as well as crop resistance to disease and pests. In fact, we may have entered a third agricultural revolution, in which dramatic further increases in farm output are made possible. The main beneficiaries will be the food-importing developing countries, where an increase in local production will be possible and for which the price of imported foods will decline. We may be on the threshold of banishing mass starvation and malnutrition as a necessary part of the human condition, assuming that food distribution systems can be rationalized.

But these promising developments are virtually certain to increase tensions among the industrialized countries, especially between the European Economic Community on the one hand and the United States, Canada, and Australia on the other. Some developing countries, such as Thailand and perhaps Indonesia, may also become important exporters of foodstuffs and thus participate in the tension. The United States and Europe are already burdened by agricultural surpluses and extensive government support to farmers. Without the introduction of some mechanism to limit the growth of food production in Europe, these agricultural surpluses will intensify as a source of friction. Despite the label *industrialized*, the United States and the European Economic Community are now the largest and second-largest exporters of agricultural goods. This goes some way, incidentally, toward explaining why both regions have become major importers of manufactured goods, to the occasional distress of their industrial workers. Countries cannot be large net exporters of all products.

7. The development of improved and less expensive drugs contributes to better health and greater longevity in industrial countries. Markedly lower birthrates and greater longevity will result in an increased average age of the population. Sooner or later these developments may force a radical change in current labor market practices that involve full-time work up to some increasingly anachronistic retirement age (such as 65), followed by a mandatory and complete retirement. Emerging labor scarcity in the United States and Europe

will result in lengthening the working life, perhaps on a part-time basis, and in easing workers into retirement. But in the meantime, especially following a period of high unemployment and great anxiety concerning job retention, there is likely to be heightened intergenerational conflict within the industrial democracies until acceptable new patterns of work can be agreed upon. The intergenerational conflict is likely to reach beyond the workplace and extend to national priorities on such questions as the environment and even foreign policy, e.g., loyalty to traditional alliances.

By reducing the growth in number of new entrants into the labor force, lower birthrates are likely to raise interest once again in enlarged immigration as a national policy in several industrial countries. If that occurs on any scale, it will of course lower the average age and increase the flexibility of the labor force. So would large-scale migration of retired workers in northern Europe to more agreeable climates, such as has occurred within the United States. This possibility is highly conjectural within our time frame, but a rapid growth of tourism to more agreeable climates is highly likely.

8. Many people fear that continued technological change, especially insofar as it arises from the introduction of computers and numerically controlled robots, will displace workers and create massive unemployment. If this were to occur on a grand scale, it would certainly affect both the domestic politics and the international relations of the industrialized democracies. Calls for protection against imports would be louder and more effective than they have ever been in the past several years, evoking corresponding calls for retaliation and a general deterioration in international economic relations.

Although pleas for protection will no doubt continue, and some will be successful, we do not believe that these will result from technological employment as that is usually envisaged, i.e., the substitution of machines for workers. (Some industry-specific unemployment may well result, however, from the changing pattern of demand—e.g., away from carbon steel—made possible by new technological possibilities.)

Technological unemployment presupposes that the demand for labor grows by less than the supply of labor. Three factors argue against this happening. First, and most fundamental, technological improvements raise incomes when they raise output. Higher incomes in general will be spent on additional goods and services, thus generating an additional demand for labor, although very likely in different places from those where the technological improvements have been concentrated. Fears of mass technological unemployment during the past 2 centuries have always proved unjustified, basically for this reason: higher productivity means higher incomes, and that in turn means increased demand for labor. Second, if households and firms do not choose to spend their additional income automatically, macroeconomic policies of governments can be adjusted to encourage further spending by either the private or the public sector. Overall unemployment is determined by macroeconomic policies, not technical change. Third, the birthrate has been declining in most modern industrial societies, to the point at which the natural growth in the labor force in the late 1990s will be very low, and in a few countries, even negative. Labor will be perceived to be in short supply rather than in superabundance. For all of these reasons, we do not anticipate the emergence of mass technological unemployment in the next 10–15 years, or even technological dislocations (which will be present) in greater magnitude than these economies experienced in the past 30 years.

9. An interesting question is whether technological developments during the next 10–15 years will, on balance, foster or inhibit the growth of international trade. Clearly, there are forces pushing in both directions. On the one hand, new materials, often made mainly from domestically available raw materials, will cut down the demand for imported raw materials. The revolution in telecommunications and computation widens the possible span of managerial control so that widely dispersed plants can be subject to direct management from a single location. Computer-aided design and production control will perhaps reduce the optimum scale of production facilities. Taken together, these changes would permit both decentralized production close to market and centralized financial control. This situation would inhibit international trade but foster international investment.

On the other hand, cheap telecommunications also permits long-distance merchandising and direct order from distant sources of supply. Declining transport costs push in the same direction as greater trade. Also, we should not think of trade as applying only to merchandise. Improved telecommunications is likely to increase greatly the international exchange of such services as investment brokerage and insurance.

Ray Vernon (1982) has addressed the ambiguities in the outcome, but he emphasizes the diffusion of new technology as a substitute for trade, both by reducing the technological gaps among the major industrial countries and by permitting worldwide financial and managerial control of local production facilities. Thus, he sees a tendency during the next decade for improved communications to reduce international trade relative to economic growth.

In our judgment, however, the world integrative and trade-promoting tendencies are likely to outweigh the trade-inhibiting tendencies, although those are certainly present as well. Unless it is blocked by government action (more on this below), we foresee that international trade will continue to grow more rapidly than world output, although perhaps with a lower gap between the two than has characterized the last quarter century.

10. The technological changes we envision will also have various impacts on the detection and control of environmental pollution. Improved capabilities in these areas will not, however, mean a fundamental change in the politics or the economics of the environment.

In the detection of environmental problems, aviation and space technologies have already played a significant role in determining the extent of deforestation in some countries or the spread of oil spills in offshore areas. Improved aerial scanning techniques may contribute to our capability to uncover and measure the extent of other forms of environmental degradation and pollution. Enhanced information-gathering techniques based on advances in microelectronics may allow us to determine the scope of acid rain deposition, to anticipate climate change that is brought on by the increase in carbon dioxide in the atmosphere, or to measure tropospheric ozone depletion caused by emissions of chlorofluorocarbons.

As technology improves our ability to detect pollution, it will also enhance our capability to monitor and control pollution at its source. In the case of carbon, sulphur, and nitrogen emissions from smokestack industries, the ability to measure emissions might lead to steps to run operations at safe periods during the week. At the saine time, the opportunities for enhanced energy efficiency are likely to have a major impact on the atmosphere. As fuel is consumed more efficiently, the amount of residual particulate matter is reduced. This will help mitigate a series of related problems, from acid rain to the "greenhouse effect."

Biotechnology promises to contribute to environmental management by allowing us to produce cleaner fuels. At the same time, new microbes are being studied to help in the cleanup of toxic wastes, that is, microbes along the lines of those currently used to clean up oil spills. There is, of course, growing concern that biotechnology will introduce a host of new environmental problems. Various publics have expressed fears about research on new forms of life, on chemical warfare, and on a variety of other genetic engineering activities. Careful regulation of experiments and research will be needed to ensure that the environmental consequences of these activities are, on balance, benign.

Technological change can affect the environment favorably or unfavorably. The development of new materials may, for example, bring environmental problems or benefits, depending on the precise nature of the materials and on how their production is managed. The key to developing environmentally safe materials lies in anticipating possible adverse impacts and in planning carefully to prevent them.

IMPLICATIONS FOR NATIONAL GOVERNMENT POLICIES

As a result of technological change, our planet is shrinking psychologically. National societies are increasingly permeable to international influences. This is not a new phenomenon, and it has not proceeded without interruption, but it is a general trend that we believe will continue. Moreover, the mobility of economic agents, especially business firms, has greatly increased with improved international communications. Yet this heightened mobility erodes the traditional control of national governments over the course of economic events. However, during the past 4 decades, publics of democratic societies everywhere have come to expect more of their governments, not less. An increasing sense of impotence with respect to control over economic events in the presence of high expectations is bound to lead to political frustration. This frustration will be compounded to the extent that national values become less homogeneous within countries owing to divergent intergenerational preferences. Another source of frustration will be what may be called technological anxiety—the sense of being behind or falling behind other nations technologically, a sense which, paradoxical as it may seem, can be present simultaneously in all major countries, as it is at present.

Since the potential erosion of government control arising from increased openness of national economies and the mobility of economic agents may not be immediately obvious, we will offer several examples of this phenomenon.

First, the openness of an economy with respect to foreign trade weakens the macroeconomic impact of fiscal policy. Actions to expand the economy, for example, will be frustrated to the extent that the resultant demand leaks abroad in the form of increased demand for imports. This will stimulate foreign economies, but not the economy that initiates the stimulus. In another example, a tax increase to reduce demand may succeed in reducing the demand for foreign goods and to that extent fail to dampen home production. The fiscal multipliers have declined over the past 20 years in all major industrial countries as these countries have become more open to international trade. This situation was made possible, in part, by lower transportation costs and better international communications.

Similarly, increasing international mobility of financial capital, due to fast, reliable international communication, reduces the effectiveness of monetary policy when, as before 1973, exchange rates between national currencies are fixed. An attempt to tighten domestic credit, for example, will simply pull in funds from abroad, thereby weakening or even undermining the intended effect of the monetary authorities. Of course, when a country as large as the United States tightens credit, it tightens world monetary conditions and thereby retains some domestic effect. But it achieves this result only by pulling the rest of the world in the saine direction, which may not be welcomed by other countries (as occurred when the United States tightened monetary conditions in 1969 and again in 1981–1982).

The introduction of flexible exchange rates between currencies restores some national autonomy to monetary policy, since the exchange rate will adjust in response to monetary tightening or loosening. That introduces a new channel by which monetary policy affects the domestic economy. For example, tightening domestic credit will lead to an appreciation of the currency, which will worsen the trade balance and thereby rein in the domestic economy—presumably the authorities' intent. American experience in the early 1980s comes to mind. Erosion of the effectiveness of monetary policy is the basic reason why flexible exchange rates were introduced, first by Britain and Canada and then by others, in the early 1970s. That introduction was a move to protect national autonomy.

But flexible exchange rates create their own problems. When an important currency appreciates or depreciates (in real terms), it affects prices and aggregate demand not only in the country taking the action but also in other countries. These spillout effects may be unwelcome, and they represent a possible source of friction between countries, as they did between Europe and the United States in 1981 and 1982. The continental European countries found flexible rates so disturbing to their national economies that they moved a long way back toward fixed exchange rates among themselves in 1979 with the establishment of the European monetary system.

These are macroeconomic effects of openness made possible by modern transportation and communications, but analogous effects can be observed at the microeconomic level with respect to government regulation and taxation. The mobility of business firms, made possible without loss of head office control by fast and reliable long-distance communication, erodes regulatory measures and, to some extent, redistributive taxation.

The creation of the Eurodollar market was a direct response to regulated interest rates in the United States and other national markets. For large transactions, banks could pay higher interest rates to their depositors and at the same time charge lower rates to their customers once they were freed from regulation. Thus, the Eurodollar market was born in the late 1950s and grew dramatically, especially in the 1970s, outside the national jurisdiction of any country. (The market was centered in London, but the Bank of England chose not to regulate it, since it was denominated in dollars rather than sterling, in which the Bank of England's principal interest lay.)

Similarly, capital or other portfolio requirements or disclosure requirements on banks and other financial institutions led to the establishment of subsidiaries in regulatory havens, such as Luxembourg or the Bahamas, to permit greater freedom of action—movement that thus weakened or undermined the regulatory intent. The obverse of disclosure is privacy. Disclosure requirements by one country may run up against privacy or even secrecy requirements of another, as occurred occasionally in tussles between the United States and Switzerland over divergences in regulatory philosophy with respect to banking.

Mobile firms can also reduce their tax liabilities by locating real or phantom operations in low-tax countries and by running their transactions through those countries in such a way that most of the profits on an international operation accrue there. Again, reliable international communication (and, where there is some physical activity, transportation) is necessary to make such tax haven operations possible. They put pressure on revenues in the home country and thereby erode its corporate tax base.

Similarly, organized crime can exploit international mobility by operating out of countries other than those where the crimes are committed—or even, in the case of politically motivated crimes, out of countries that deliberately provide sanctuary and perhaps even support to the criminal agents.

Product regulation is not subject to the same erosion from mobility, since a country can require that all products sold in the country, including imports, meet the same regulatory standards. (There will be a temptation to make such product regulation be "nontariff barriers" to imports, as Japan has done in the past, but that is a different issue.) Moreover, some regulation of productive activity can be even more effective when international mobility is high, but only by creating other problems. For example, when a government imposes pollution standards or occupational health and safety requirements on productive activities within a country, a potentially mobile firm has two choices: it can comply with the new regulation or standards, or it can move incrementally or even totally to another country. In either case, the objective of the regulation has been achieved—to reduce domestic pollution or to improve the health and safety of the national working population. But moving a firm abroad may cause dislocation and other hardships to the workers left behind. The receiving country may appropriately have lower standards because, for example, its lower average income gives rise to a different ranking among national objectives—more to income-raising employment, less to occupational health and safety—than that in the high-income country. Or its rivers and atmosphere may still offer viable channels for disposal of waste effluents without causing undue air or water pollution. Both countries, therefore, may be made better off, given their respective circumstances and preferences.

However, there is a risk that high mobility may inhibit some countries from imposing pollution or safety regulations for fear of losing firms abroad or for the sake of attracting internationally mobile firms. These countries thus become regulatory havens.

Responses of Governments

All of these consequences for governance arise from mobility, which in turn is due to improved technology, especially in transportation and communications. All of these effects can be observed in the recent past, but all are likely to become more pronounced in the future, as transportation and communications continue to improve both in quality and in cost. How do governments respond? We characterize the possible reactions under four headings: defensive, accommodative, aggressive, and cooperative.

Defensive Responses

Defensive responses involve attempts by governments to stop erosion of the efficacy of their actions by steps that reduce the openness of their national economies, for example, by reducing the mobility of firms or funds. Many countries place limits on the international movement of capital, and even such free-enterprise countries as the United States and West Germany resorted to such devices in the 1960s in order to reduce the leakages abroad arising from divergent domestic monetary policies. As noted above, the move to flexible exchange rates in the early 1970s can be interpreted in the same light: to reduce the actual movement of capital with a view to restoring some effectiveness to domestic monetary measures. Defensive responses can also take the form of discriminatory taxation, as when Canada denied full taxation deductibility to Canadian firms that advertised in U.S. media that reached potential Canadian customers.

To protect privacy, several countries have placed severe restrictions on certain movements of data across their national boundaries. One is even beginning to hear on both sides of the Atlantic about the need for secrecy on scientific developments having possible commercial application, on the grounds that the free flow of information represents a loss of potential competitiveness. Again, this would represent a defensive reaction that, if implemented, would slow down scientific advance to the detriment of all countries (Thomas, 1984).

Accommodative Responses

Governments may also engage in accommodative responses, by which we mean that they do not resist erosion of traditional policy measures, but rather adapt their measures to the new prevailing circumstances. In particular, they take advantage of the new, higher mobility by trying to entice internationally mobile firms to locate in their countries by offering specific tax advantages or by incurring some of the initial investment costs with public funds. If conventional fiscal policy cannot create much employment by expanding aggregate demand, tax incentives to new foreign employers may be able to do so. The proliferation of regional policies in Europe is the most general example of the use of the special investment incentives, although many developing countries also provide fiscal incentives to new foreign firms, as do states and provinces in the United States and Canada.

Another example of accommodative responses is the reduction of general regulations or taxation to attract or hold internationally mobile firms. The classic example is "flags of convenience" in international shipping, whereby Liberia, Panama, and other countries encourage local registry by imposing less rigorous safety standards on ships and less onerous taxation on their owners than do the traditional maritime nations. But the analogue of flags of convenience can now be found in other areas as well, most notably in banking. Even the United States, which has been among the most rigorous regulators of banks for the past half century, recently responded to the loss of banking activities overseas by permitting international banking facilities in New York and other centers that fall outside the normal regulatory framework of U.S. banks. This relaxation was designed to bring back some banking activity to the United States that had migrated elsewhere in response to more liberal regulatory environments. The Bahamas and Grand Cayman are "nameplate" centers for international banking, and Bermuda has recently become a major center for the reinsurance industry.

Some countries are reluctant to impose pollution standards, despite the need for them, for fear of driving away some firms. With ever greater mobility, we may find a growing competition among governments in regulatory laxity. Whether that is good or bad is a complex question not addressed here, and the answer depends very much on the particular circumstances of each case. For example, many readers will consider laxity in pollution standards undesirable, but such policy competition among governments may result in more competition between international airlines or even, eventually, for international communication as travelers or business customers shop around for the best deal among several competing possibilities. This process could gradually break down the national monopolies of airlines or postal, telephone, and telegraph organizations in Europe and elsewhere. Our main point is not that this is a desirable or undesirable process, but rather that it will be a condition with which governments will increasingly have to cope.

Aggressive Response

Governments may also engage in aggressive responses, whereby in the face of decreasing effectiveness in their actions they try to extend their reach to cover the escaping parties. The principal actor here has been the United States, in such areas as antitrust law, disclosure, and foreign policy restrictions on exports. Regular trips by businessmen abroad make price-fixing or other anticompetitive collusion easier than it was in the past and thus make discovery of critical information by the Antitrust Division more difficult. Not to be undone, the Antitrust Division has from time to time subpoenaed information abroad, to the considerable irritation of the governments of the countries in which the information is located. Predictably, these countries' leaders have objected to the extraterritoriality of the U.S. government action. Similar problems have risen with Securities and Exchange Commission (SEC) disclosure requirements and with commodity futures regulations. But the most celebrated example concerns the Soviet gas pipeline, where the United States not only prohibited export of American products but also prohibited foreign firms under U.S. license from selling their products to the Soviet Union. The British and the French governments, followed by West Germany, responded by ordering their firms to ignore the U.S. orders, thereby putting the firms directly in the middle of a major jurisdictional conflict.

The United States provides the most dramatic and the most frequent examples of an aggressive response to growing interdependence, but it is not alone. Both Japan and Switzerland have taken steps to prohibit the use of their national currencies as currencies of denomination on securities issued outside their respective countries. Export subsidies, direct or indirect via credit terms, can also be interpreted as an aggressive response, in this case to stiff international competition, often technological in origin. We include under this heading the agricultural export subsidies of the European Economic Community, for although farm output is not especially high tech, the incredible increase in agricultural productivity is due to the application of modern technology to agricultural production. Similarly, governments compete in giving favorable export credit terms, especially for high-technology projects, such as telecommunications equipment or aircraft, on which national prestige has been staked in terms of technological competition.

Cooperation

A final type of governmental response is cooperation with one another to overcome the erosion of policy measures due to greater mobility of firms and funds. The essence of such cooperation involves enlarging by international agreement the jurisdiction covered by the actions of governments to encompass the international domain over which the funds or firms are mobile. The mechanisms range from formal undertakings through informal agreements to nonbinding guidelines. Thus, attempts have been made from time to time, most notably at the Bonn economic summit of 1978, to coordinate monetary and fiscal policies among the major countries. Although each country faces large leakages from its actions if acting alone, that is not true for all major countries acting together. Attempts to establish internationally agreed-upon minimum standards—for example, on pollution or on controls over exports to Communist countries—represent moves in the same direction. As a result of difficulties arising in international banking during the past decade, the monetary authorities of the leading countries have taken tentative steps together to collect and exchange information on their major banks on a coordinated basis. Other examples could be enumerated. Indeed, from this perspective, the formation of the European Economic Community itself was an attempt to surmount the limitations that individual European governments increasingly felt, or recognized that they would feel, in an increasingly interdependent world.

A combination of all four responses can be seen in the approach of governments to high technology. Technological anxiety can be found in all major countries to various degrees—anxiety at being behind or at falling behind or at not maintaining an adequate lead. This anxiety is understandable in the military arena with respect to one's likely adversaries, and it is understandable among business firms concerned with their close competitors, but technological anxiety in the commercial field now also extends to governments, to the point at which they have taken a series of steps and are contemplating others to improve or maintain the technological standing of their nations' products in commercial markets. These steps go well beyond the traditional and widely accepted government role in financing basic research and in supporting an educational system that produces technologically qualified graduates. It now often includes not only applied research—research that is close to possible commercial application—but also the development of the commercial products themselves, as in the case of nuclear power plants, supersonic aircraft, and the airbus. Government support is also being given to the development of very large integrated circuits. Japan and some European countries are supporting the development of future computers. These developments potentially place governments right in the middle of commercial competition.

Governments are also directly involved in commercial competition on world agricultural markets by a combination of dramatic, technology-based increases in agricultural productivity with political commitments to farmers to maintain minimum prices for their agricultural output. These two elements are incompatible in the long run, but in the meantime they give rise to heavy budgetary expenditures for farm income support, combined with a strong effort to export surpluses in order to relieve the budgetary costs.

Finally, governments are beginning to speak about controlling the export of technology, including the results of applied research, in order to preserve national competitive advantages—an exercise that in one form or another has been tried throughout history and has usually failed whenever people could travel freely.

IMPLICATIONS FOR FOREIGN RELATIONS

The observations above paint a picture of a clash between some technological imperatives and the formulation and execution of policy at the national level. National governments will experience increasing frustration, leading to conflict between governments that share similar values, political systems, and economic structures. It is worthwhile recalling the values common to most modern industrial democracies: a strong commitment to democratic forms of government, to protection of individual freedoms, and to international security with respect to the Soviet Union and other possible threats (including international crime and terrorism). These countries also have a common interest in integrating other countries into this system of common values as their levels of economic development and political participation permit it. There is always a risk that these basic common values and objectives will get lost in the welter of specific conflicts that are likely to emerge from the tensions between the internationalizing effects of technological developments and the traditional practice of making decisions at the national level. We identify what are likely to be the most salient sources of conflict, followed by discussion of possible areas for international cooperation. Some of these areas have been alluded to above.

Possible Areas of Conflict

We are poised on the edge of what may be a third agricultural revolution. The first occurred in the eighteenth century. The second occurred in the 1950s and 1960s with selective breeding, the systematic application of chemical fertilizers and pesticides to crops, and the scientific feeding of livestock and fowl. Bioengineering may increase the productivity of agriculture much further, although its full impact is likely to fall outside of our 10–15-year time frame. This will be a boon to those countries that are in food deficit, permitting them to feed more of their growing populations from domestic production and to buy on world markets more cheaply. But it will create conflict between countries whose exportable surpluses grow beyond the ability of world markets to absorb them. In our time frame we see agricultural surpluses, not shortages, as the endemic problem, although that does not preclude regional shortages and short periods of overall shortage as well. The tendency of production in temperate areas to rise more rapidly than demand in developing countries will put ever greater strains on farm support programs and will heighten the competition for export markets that, because of national farm support programs, will inevitably engage governments in direct competition with one another.

The central problem at present is the European Economic Community, which maintains agricultural price supports well above world market prices, with no limits on production. The result has been a substantial increase in agricultural output, often, as in the case of sugar and wheat, beyond the needs of the European Economic Community, resulting in surpluses that must be subsidized to be sold into world markets. The European Economic Community took the first tentative steps in 1984 to lower agricultural price supports and to place limits on production entitled to the price supports in sugar and dairy products, but it is a very modest start, and progress in this direction is likely to be slow in the face of resistance by domestic interests.

Japan also has some prices well above world levels, and without its new production controls it has developed a surplus in rice production—an ironic development for a land with so little arable land relative to its population. But the problem also exists in the United States, where price support levels require ever tighter production controls to avoid burgeoning surpluses. Until countries develop policies that are sustainable in the face of rapidly advancing technology, frictions over agricultural policy are likely to be a major irritant in relations between the advanced states. One resolution that is often mentioned is for agricultural surplus areas to give away their food surpluses to the world's destitute, but that would require much larger continuing budgetary support that now seems feasible, and it would also require large investments in the distribution systems of potential receiving countries, mainly in Africa. It would have the more troublesome long-term consequence of depressing agricultural production in the developing world.

Governments will also find themselves in conflict over the development and commercialization of high-technology products. Concern over technological gaps or loss of technological lead propels governments to take steps designed to correct the alleged ailments. Much of this is useful and augments the world's fund of technological knowledge, but governments are tempted to go beyond applied research and on into the development of commercial products. Once committed to them, they tend to take the resulting products to the production stage, whether that is economic or not. The most celebrated illustration is the British-French Concorde supersonic aircraft.

The conviction that there should be national production of nuclear reactors and computers and sophisticated telecommunications equipment has spawned a whole array of government measures to achieve these aspirations. Japan has received much publicity for its public support of so-called fifth-generation computers. Our impression is that the ratio of publicity to action attending that program is exceptionally high, but it has served the purpose of providing a focus for development efforts by Japanese computer firms. In Europe, government attention and funding have focused more on the civil aviation industry, and in particular on the development of the airbus series. There is much less direct support for product development in the United States, but some occurs indirectly, through the defense industry, and explicitly at present for developing very-high-speed integrated circuits. Many of the newly industralized countries provide government support for national product development, often through state-owned enterprises.

Direct financial involvement in product development and commercialization creates strains when it occurs in competition with private firms that must finance their own R&D and start-up production costs. Further strains, and even direct competition between governments, arise when public credit is used to subsidize the export of high-technology products. An example was the Austrian-French package for sale of modern telecommunications systems to Egypt. The situation is further complicated when the firms involved, while commercial in purpose and organization, are government owned, as is increasingly the case both in Europe and in many developing countries. Infusions of new government equity capital can look and behave like a subsidy when the firm is running at a loss, as often happens. Americans tend to forget, when criticizing these arrangements, that state-owned enterprises are often required to maintain uneconomic levels of employment or to pursue other social objectives that increase their costs. The ambiguity of their role in the presence of commercial competition is a continuing source of friction. This problem arises as much in traditional industries, such as steel, as in high-technology industries.

Competition for high-technology success also takes the form of protectionism. If a country wants a particular activity, it is reluctant to buy abroad and encourages or requires state agencies and enterprises to buy the high-technology products from local suppliers. Recently, we have had the celebrated case of NTT (the Japanese telephone system), with its favored suppliers, that even excluded some Japanese firms. In another example, the West German government puts pressure on universities (which are governmental bodies) to buy West German-brand computers. This practice not only fragments markets and raises costs, and incidentally may put West German universities at a competitive research disadvantage, but also represents a source of tension when asymmetries are involved—as when U.S. universities are free to buy anywhere.

A more dangerous form of protectionism has recently surfaced. It concerns inhibitions on the free flow of ideas—not merely proprietary information within particular firms but also more generic information available to specialized professional communities, such as new developments in the physics of surface effects or in biogenetics. Since rapid progress in any area typically depends on the interactions of many specialists, restricting information will not so much preserve commercial advantage to the restrictive country as reduce the overall rate of technological advancement.

One aspect of competition in high-technology items that is sufficiently important to warrant separate identification concerns the sale of high-technology products to the Soviet Union and other Communist countries. The starting point is the philosophical difference between what may be called the modal American view and the modal European view toward trade with potential adversaries, and especially with the Soviet Union. There is, of course, a wide spectrum of views within each area, but the modal American view sees trade as being a great benefit to the Soviet Union and of only marginal benefit to the West. Trade in high technology or products embodying high technology runs the risk of narrowing the Western lead over the Soviet Union in military technology, a lead that is crucial to successful defense of the West. These American views are reinforced by a historical tendency of the United States to boycott its adversaries on moral grounds.

The modal European view sees the benefit of trade with the Soviet

Union as being more balanced, and in addition sees trade as a tension-mitigating activity because it gives the Soviet Union a stake in good relations with the West and in improving lines of communication between the West and the Soviet Union. It is thus helpful in preserving world peace.

These differences of view are aggravated by so-called dual-use technological advances. Many technological developments, particularly those in electronics and in new materials, have both military and nonmilitary applications, with the balance between them varying substantially, depending on the particular product in question. Given their perspective, Americans tend to emphasize the potential military applications of any new development, however small it may be. Europeans, in contrast, while desiring to maintain the Western technological military advantage, are inclined to require a direct and consequential military use before they are willing to restrict sales to the Soviet Union.

Tensions between the United States and Europe have existed over this issue—and over the different but related tendency of the United States to use export controls for foreign policy and not merely for national security purposes—for some time, but they are likely to be greatly aggravated as general technologies with wide military and nonmilitary uses become available, particularly in the realm of microcircuitry. Successive American administrations will want to define restrictions on high-technology exports to the Soviet Union broadly, whereas the Europeans—propelled in part by their desire to develop competitive high-technology industries at home and knowing the American proclivity for restricting U.S. exports to the Soviet Union—will want to define them much more narrowly.

A related issue concerns the sale of sophisticated military equipment, on which there is no disagreement concerning the Soviet Union and its allies, to developing countries, including China. Again, although there have been important fluctuations in U.S. policy from administration to administration, the United States is inclined toward greater restrictions than are European countries (and Israel). These countries wish to spread the fixed costs of their arms industries over larger sales than home forces alone can absorb, and in addition they welcome the incremental export income, employment, and foreign policy advantages that flow from arms sales. Each new generation of weapons, especially aircraft, raises the issue anew.

The increased mobility of firms, combined with different stances toward regulation and corporate taxation by different countries, will give rise increasingly to jurisdictional disputes of various kinds. Who exactly is responsible for oversight or support of an Italian bank operating in U.S. dollars out of London? We have already alluded to occasional efforts by U.S. regulatory bodies—the SEC or the Antitrust Division of the Department of Justice—to extend their jurisdictional reaches into other countries in pursuit of their assigned tasks. With many U.S. firms producing in many countries and diffusing their technology abroad, it will be tempting for the United States to try to restrict high-technology exports to the Soviet Union or to other target countries from other countries as well as from the United States, as it tried to do in the case of the Soviet gas pipeline.

The latest source of dispute of this nature is the effort by several American states, led by California, to levy taxes on the worldwide income of corporations operating in a state—taxes proportionate to the ratio of corporate activity in that state to its worldwide activity. This is the so-called unitary tax. Companies and their home countries have objected strongly to the use of the unitary tax, without, however, acknowledging the fact that worldwide corporate activity really does create a problem for tax authorities, since the freedom to manipulate intracorporate transactions across national boundaries provides corporations with opportunities for minimizing their tax burdens by shifting profits from high-tax to low-tax jurisdictions. The unitary tax is not the best solution to this problem, unless it is uniformly applied, but merely defensive reactions by other countries may be counterproductive. Action and counteraction by nations defending their sovereign rights are anachronistic when firms have wider domains of mobility than do national authorities.

Economic Policies

Yet another area of potential conflict concerns the impact in other countries of domestic economic policies, especially macroeconomic policies. As improved technology opens national economies more and more to one another, the action of one major country exerts greater influence on other economies, and this can be a source of tension between countries. Recent examples concern the European perception that U.S. oil price controls in the late 1970s were impeding oil conservation in the United States, to the detriment of Europe, and the situation in the early 1980s, when very tight U.S. monetary policy aggravated unemployment in Europe and limited the room for monetary action by European countries. On its side, the United States felt it could not stem the world oil shortage or the 1974–1976 world recession alone and needed the active support of other major countries, notably Japan and Germany. The absence of support for this and other efforts to address problems of the world economy has been a source of conflict. The need for joint action if the advanced states are to be effective requires international cooperation.

In these as in other areas of prospective friction between the advanced industrialized countries, an underlying theme will be the desire to maintain cultural values and a degree of cultural identity. At the government level, this will be closely bound to fears of losing aspects of national sovereignty and economic independence. Indeed, it is often difficult to determine whether a motive is economic or cultural. For example, is the Canadian government's insistence on promoting separate media and on restricting the access of U.S. magazines and television to the Canadian market an economic or a cultural policy? There is no clear dividing line.

The advance of new technologies is a particular threat. Not only do they tend to promote world markets and consumption of similar goods, but they can also foster a common life-style across national borders. Hence, governments have developed a variety of defensive responses in the form of restrictions on access to or the movement of data and television programming across national borders. The arguments made include the need to protect the privacy of the citizens in the face of impersonal multinational corporations that might exploit the information to their advantage. Indeed, the loss of privacy is a genuine concern in the face of expanded information-gathering, data storage, and transmission capabilities.

Of particular note, as Europe has moved toward closer economic integration, national and even regional groups have responded vigorously to preserve their identities. Not only does each country want to maintain separate national industries (with access to the "European market"), but each also continues to strive to maintain its language, traditions, and cultural identity. The insistence of each of the countries on maintaining separate satellite broadcasting systems, for instance, has resulted in redundant capacity and overlapping broadcast zones.

Possible Areas of Cooperation

In light of the predictable sources of friction in the future, the search for opportunities to control conflict and develop patterns of cooperation becomes desirable. Rather than react to technical changes by expanding the scope of government control or resisting the encroachments of other societies, a nation's goal should be to use technological capabilities beneficially to enhance the quality of life for its citizens.

Although national preoccupation with sovereign prerogatives will not disappear, increased attention might be paid to securing predictability and mutual gains through efforts to rationalize important international transactions. The goal would be to encourage competition within an accepted cooperative framework. Gains would flow from reducing the high costs of duplicate efforts and of barriers to the flow of goods, knowledge, and information. Inevitably, all countries may find that they lag in the development of some technologically advanced goods or services; that situation would reflect specialization in innovation. Where the goods and services are freely traded, however, citizens can benefit from innovations no matter where they occur. As long as a country excels or competes successfully in at least some products, the economic welfare of its society will be enhanced.

The advanced countries interact today in a wide variety of areas, ranging from broad political discussions to narrowly focused technical meetings. The annual economic summit meetings of the heads of government of the United States, Britain, Canada, Japan, France, Germany, and Italy have perhaps the broadest political agendas. These meetings have given high-level impetus to cooperation in trade, energy, finance, macroeconomic management, and many other areas. On a day-to-day basis, the advanced countries address common problems in OECD, the COCOM, the North Atlantic Treaty Organization, the International Energy Agency (IEA), and the London Suppliers Group (suppliers of nuclear fuel). These organizations provide the opportunity to deal with problems of special interest to industrialized countries. They also offer a chance for the industrialized states to confer on problems of global concern that are addressed in other, larger organizations. As the newly industrialized countries develop, it is important that they have the opportunity to join the industrialized democracies in those groups and organizations dealing with issues of common interest.

Examples of global organizations where the advanced industrial countries must deal with other countries range from those having focused discussions, such as the World Intellectual Property Organization (dealing with patents), to the United Nations Committee on Trade and Development, which subsumes a broad range of economic issues. International economic organizations that are critical to developing common or cooperative approaches include the General Agreement on Tariffs and Trade, the International Monetary Fund, and the International Labor Organization, among many others. If the advanced industrial countries are successful in developing frameworks for cooperation in these and other organizations, the benefits of technological advance will be widely dispersed.

A promising area for promoting cooperation is that of early agreement on common technical standards. We have seen the difficulties posed by the differences in electric currents and outlets adopted by different countries. In addition to the inconvenience posed to the traveler who carries items such as electrical shavers, travel irons, and hair dryers, the differing technical standards serve as a barrier to trade.

Once divergent systems are established, it is extremely difficult and expensive to undo them. The adoption today of uniform standards for electric systems, for example, would be prohibitively expensive. It is important, therefore, to develop common technical standards for new technologies as they come on line in order to avoid further fragmentation of markets. The development and marketing of computers on a global basis would be significantly facilitated by the adoption of standards for compatible hardware and software.

A basic change that will be conducive to global markets is the general acceptance of the metric system. The United States has been moving slowly in this direction. The costs of the retooling required will probably be offset by the greater interchangeability of goods. From minor items, such as compatible threads on nuts and bolts, to more consequential goods, such as automobiles, the United States would find itself in a far better position to market its products throughout the world.

Similarly, attention must be paid to developing common standards in the areas of health and safety in those cases where no useful purpose is served by national standards. Divergent regulations have sometimes deliberately or inadvertently restricted trade, particularly for pharmaceuticals. The loser in this situation is the consumer, who, for example, finds that he or she cannot purchase at home a medicine that he or she discovered abroad. It is particularly important that common regulations be developed for laboratory requirements, testing procedures, lengths of clinical trials, and so on. Biogenetic engineering promises rapid advances in agricultural production, and it is important that barriers to the widespread dissemination and enjoyment of new developments be reduced or eliminated where possible.

Another area where mutual benefits can be derived from cooperation is joint financing of expensive R&D. The space shuttle and other space projects are ideally suited for international cooperation. The costs of space work and travel are high. The scientific benefits of the evolving knowledge of the universe are universal. Apart from telecommunications, the economic benefits of space are uncertain, at best, although some possibilities exist. With such a balance of costs and benefits, space technology is ideally suited for cooperative R&D. High-energy physics, exploring the nature of matter, represents another such area.

Other areas for cooperative funding and division of labor in R&D include new energy technologies and, perhaps, new materials research. Nuclear energy has been a consistently costly form of energy, and work on the breeder reactor, effective nuclear waste disposal, and nuclear fusion is particularly expensive. Similarly, the development of capabilities to liquefy coal is prospectively very costly, with widespread benefits if we can learn to do it economically. Cooperative funding and sharing of research in these and other areas will not only offer economic benefits but also contribute to a more cooperative international climate in dealing with any disruptions in oil supplies. Some aspects of research in new materials may prove to be equally promising areas for joint financing.

The special nature of oil and gas makes them ripe for international cooperation beyond cooperative R&D. The concentration of supply in the hands of a few countries in a politically volatile area and the global dependence on the product imply extreme vulnerability to supply disruptions. We have seen that competitive responses to supply disruptions, as in 1979, have severe economic costs. No single nation can bear all of the costs of planning for interruptions of supply. One promising path for dealing with possible supply disruptions is cooperation in building and planning for the use of emergency stockpiles of oil. IEA has been the forum in which such planning has moved ahead. Even with the recent decline in oil prices, the costs of stockpiling are high. They can only be justified in light of the potential risks if other nations are taking similar steps within a cooperative framework.

We drew attention above to the alteration of national macroeconomic policy as economies become more open. An obvious, if difficult, solution to the problem is for major countries to cooperate in framing their macroeconomic policies. Cooperation may mean acting in the same direction, but not necessarily; it would have been globally appropriate in 1982–1983, for instance, for the United States to have pursued a tighter fiscal policy while Japan and several European countries pursued a somewhat looser one. But in either case, coordinated action will increase the effectiveness of the actions in achieving desired macroeconomic objectives.

Coordination of macroeconomic policies is not easy in democratic societies. Legislatures are the ultimate arbiters of taxes and expenditures, whereas foreign policy is carried out by ministers. The annual economic summits, supplemented by OECD ministerial meetings, provide occasions for comparing economic assessments and intentions and, where appropriate, altering intentions in collaboration with others. It would be a modest but useful beginning.

An additional area of cooperation between advanced industrialized countries concerns their foreign policy stance toward the rest of the world—that is, toward the developing countries on the one hand and the Eastern bloc on the other. Whether the issue is aid, trade, or military readiness, countless opportunities arise for friction and policy disagreement. COCOM can serve as the arena for resolving disputes over exports of high-technology goods to the Eastern bloc. As countries promote their high-tech sectors to gain a greater share of the world market, the competition for markets will intensify. It is inevitable that differences over which products should be put on the proscribed list of exports will grow out of different perceptions about the risks, dangers, and benefits of dealings with the Eastern bloc. The costs of not resolving these types of differences within a common framework are too high to ignore.

CONCLUSION

The future holds many opportunities and many dangers. In the preceding pages we have limited our attention to those that stem from technological developments in six areas—energy, new materials, aviation and space, computers, telecommunications, and biotechnology—and we have focused largely on relations between industrialized states rather than internal developments or relations with other parts of the world. This narrowed beam necessarily omits fascinating issues, such as the impact on family life, on relations in the workplace, or on national politics, except insofar as those may have some bearing on relations among countries.

On the basis of our projections, we find that technological change will act as a unifying force. In the case of private industry and commercial and financial institutions, technological advance acts to bring the world closer together. As the world shrinks in terms of travel and information flows and in terms of business and personal contacts, interdependence is fostered, but greater interdependence clearly breeds a host of problems. Perhaps the most obvious problem is government reaction to maintain economic and cultural autonomy. Indeed, in the years ahead, national, political, and legal institutions will be the principal forces working against the unifying impact of technology.

There is no philosophical case to be made in favor of increased integration of the world or in favor of maintaining fragmentation. Neither unity nor diversity per se can be evaluated in the abstract, independently of some understanding of the benefits. The goal should be to improve the quality of life for the individuals in the societies under consideration. To that end, some greater integration may serve an important purpose in providing better quality and less expensive goods and services. Diversity has the value of allowing competition to continue as a stimulating force. The areas of cooperation that we identify are designed simply to allow the construction of a mutually beneficial framework within which integration and diversity can be managed.

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Technological Advances—Their Impact on U.S. Foreign Policy Relative to the Developing Nations

C. W. Robinson

We have benefited in this symposium from the wisdom and expertise of leading representatives from science, academia, and industry, who have projected future developments in six areas of advanced technology. The purpose of this paper is to assess the impact of these developments on U.S. foreign policy in our relationships with the developing world—often referred to as North-South relations.

We have been forewarned by these experts that there will be a relentless flow of new technology, posing a continuing challenge for all of us. There is also the implication that this flow will be at an accelerating rate, promising not only benefits but also ominous threats. The changes in our society will continue to develop at a faster pace as well, creating even more complex challenges in our relationships with the developing world. Certainly, the need for new policies that will reflect these changes will be imperative, and we will have to strive to develop such policies in a continuous process of adjustment.

In analyzing the impact of technology advances on North-South relations, it is important to define first what we mean by the "South" and the "North." For purposes of this analysis, we make an arbitrary distinction regarding the South by concentrating on those nations in the developing world, commonly known as Third World countries, that are in an early stage of economic development. This excludes the newly industrialized countries. Also excluded are China and the oil-rich nations of the Middle East, which, although developing countries, have characteristics sufficiently different to eliminate them from consideration in this paper. The North, of course, refers to the economically developed and industrialized nations, commonly known as First World countries. This paper, however, focuses primarily on the policies of the United States as the North's leading representative.

We can approach the analysis regarding the impact of the technological revolution on North-South foreign policy in three distinct steps:

- First, we must understand the nature of the economic and political environment in the South.
- Second, we should reflect on the economic, political, and social impacts of technological advances on the South.
- Finally, we must assess the challenge that the changes from these advances in the South will impose on the foreign policy of the United States.

THE DEVELOPING WORLD ENVIRONMENT

Perhaps the single most important source of the growing North-South conflict has been the South's ideological approach to international relations, labeled since the early 1970s the New International Economic Order (NIEO). If, as Julius Nyerere has said, "socialism is a state of mind," then the NIEO may be properly referred to as an attitude. The NIEO is based on the belief that the North, composed of former exploiters and colonizers, owes restitution to the South for past transgressions. This restitution ethic permeates the South's negotiation position on all issues. It is manifested by a negative attitude to all foreign relations proposals by the North that do not promote, or at least acknowledge, the responsibility for such restitution.

Demands of the South

The wave of antagonism of the South toward the North probably reached its peak in Nairobi at the fourth meeting of the United Nations Committee on Trade and Development (UNCTAD IV) in the spring of 1976. This event could be characterized as 30 days of armed conflict—the South armed with demands that appeared unreasonable but, in any event, unrealizable, and the North equipped with firm arguments opposing these positions, which it considered to be counterproductive and an attack on the existing global economic system.

The State Department approached this session with the idea that it would lead the industrialized world in an effort to reflect sensitivity to the demands of the developing world while continuing to maintain a position supportive of the world market system. To develop a formal position in advance, the department faced the inevitable problem of gaining support from other government agencies. This proved to be almost as difficult as negotiating with the developing world at Nairobi. Some in the administration supported reasonable flexibility within the basic rules, whereas others felt that any movement to meet even legitimate concerns of the South violated basic principles and promised disaster. As a result, the State Department plan was largely emasculated, and the U.S. position presented at Nairobi was neither functional nor marketable. In spite of this, the U.S. delegation made every effort to gain time and calm the emotional seas at that meeting. They concentrated on the two major issues pursued aggressively by the South, issues that have a bearing on our current interest in assessing the impact of technological advances on relations with the developing world:

1. The South made a concerted effort to establish a "common fund," a euphemism for socializing natural resource development on a global basis with central planning controlled largely by the source countries, that is, the South. The United States and other industrialized nations responded to the demand for a common fund by resisting the basic concept of international control of resource development. At the same time, they accepted the idea of several common funds by agreeing to discuss price-stabilizing formulas for specific commodities. They insisted, however, on joint administration by both producers and consumers in any such program. Unfortunately, this effort to move partway in seeking a compromise with the South proved abortive. Nevertheless, the North clearly established the limits beyond which it would not move in socializing global resource developments.

2. The South made a strident demand for transfer of technology without meaningful compensation, to erase the past sins of economic exploitation by the North. The second major demand of the South at Nairobi leads directly to the subject of this paper: technology transfer and its impact on foreign policy. The State Department's lead in developing the U.S. position in this area gives recognition to the impor-

tant impact of technological advances on our relations with the developing world. In the final analysis, this impact translates into a need for new foreign policies.

The U.S. position at Nairobi in 1976 reflected three coordinated approaches to technology transfer. First, it proposed a basis for making available to the South current developments in high technology that were largely controlled by the North. For instance, satellite-based programs for accumulating and disseminating information were offered on highly concessionary terms. This proposal was received favorably by the South, which recognized it as a first step toward a possibly wider range of services that might allow the developing nations to skip over the more tedious and painful effort required at a similar stage in the development of the industrialized North. Thus, the proposal was viewed as an important gap-closing measure.

Second, the U.S. position stressed the importance of joint educational and training programs for the South to expand the understanding of potential benefits from the application of new technologies. Such programs would provide better knowledge of the factors important in selecting specific technologies that could offer optimum benefits, given the prevailing conditions in each country. Although far short of the South's demand for free technology, this too proved to be a successful effort. It provided assurance that the United States and other industrialized nations were prepared to contribute to this important facet of technology transfer.

Third, the U.S. position stressed the importance of the private sector's role in technology transfer and proposed a "political risk insurance" program to encourage new flows of capital investment into the South. It was pointed out that since most of the technology that the developing nations were seeking was controlled by the private sector, it was essential to create an atmosphere in which individual companies would contribute not only capital funds but also management, technology, and access to world markets. The U.S. position emphasized the importance of minimizing political risk to achieve this objective and suggested a program for insuring this risk through a multilateral organization, such as the World Bank.

This concept was rejected by the South on the basis that it represented a form of neocolonialism that would impose on the developing world new obligations to a multilateral organization and thus would represent a sacrifice of sovereignty. Although this was neither the intent nor the probable ultimate outcome of the U.S. position, the basis for such opposition was understandable in light of the South's ideological predilection. Despite the lack of success in this effort, it is likely that something along this line will ultimately evolve as a way in which new private investment flows could be encouraged, with an accelerated transfer of technology to the South.

Let us now turn to the broader challenge that we face in the developing world. Unless we understand the economic and political conditions in that world and are sensitive to the strains that exist in North-South relationships, it will be fruitless to consider the impact of new technology and its challenge in terms of foreign policy. The following discussion summarizes some of the basic conditions that must be dealt with in the South.

Death of Colonialism

In the 4 decades since the close of World War II, we have seen the death of colonialism throughout the world. This has brought about an unprecedented change not only in terms of the fundamental characteristics of world politics and economics but also in terms of the speed with which the change has occurred. During this period we have experienced a quadrupling of independent nations, from approximately 40 to over 160, a rate of change never before experienced in world history. New nations have gained independence with boundaries established, in most cases, by historical accident and without economic rationale. This dramatic change could be characterized as a historical discontinuity with an impact on international relations that we have not yet begun to comprehend.

Economic Consequences

These newly independent countries gained an initial lift, in both emotional and economic terms, from expropriation of foreign investments, or at least from the assumption of control over the profit potential in foreign-owned assets. The lack of managerial experience in many of these countries, however, has resulted in a continuous erosion of the economic infrastructure as well as in the serious deterioration in profitability of companies formerly owned and controlled from abroad. The severing of the umbilical cord of colonialism has been painful and extremely costly for most of the parties involved. The result is that today we see many countries throughout the developing world that are economic "basket cases." They have little hope for rapid growth and no current substitute for a colonial power with special interests in the country from which to seek economic assistance. This, of course, poses an increasing burden on the multilateral financial institutions established by the industrial world to deal with these issues.

South-to-North Emotions

There has been an emotional response in the South, as manifested by the NIEO attitude, partially resulting from a growing recognition of the increasingly desperate economic conditions under which the South now operates. Since UNCTAD IV in 1976, these nations nonetheless seem to have developed a more realistic appraisal of their position and a recognition of the need to deal in a more sophisticated way with the developed nations of the world. They have a greater appreciation of the need for foreign loans, although they have a continued resistance to "conditionality"—the strings attached by multilateral financial institutions and commercial banks. This growing maturity has led to brinkmanship in negotiations as both sides seek to achieve their respective goals while avoiding the rocks and shoals of international financial default.

Oil Crisis

The oil crisis further exacerbated the problems of the developing world. Its first impact was an increase in energy costs for non-oil-producing nations, a situation that imposed a serious burden on the economies of those nations and further strained their foreign exchange balances. Second, and perhaps more significant in the long run, many of these nations were both beneficiaries and victims of commercial banks' efforts to recycle Organization of Petroleum Exporting Countries (OPEC) surplus funds. This often resulted in excessive borrowing for projects that were of questionable value. As OPEC funds available for recycling decline and commercial banks become more concerned over existing loans, the financial stability of the developing world appears increasingly threatened.

Financial Crises

We now face the possibility of financial defaults in the developing world, resulting in part from the decline in new lending to service existing loans. The commercial banks will not be as aggressive in lending, and financing from multilateral institutions will be more difficult to obtain. Furthermore, financing from both will be subject to political conditions that will be increasingly onerous and difficult to fulfill. Perhaps the threat of a major financial breakdown will encourage the industrialized nations to recognize the need for greater flexibility and support for the developing world.

Interdependence

The growing interdependence between the nations of the world is itself a product of the accelerating technological revolution since World War II. Certainly, our capacity to exchange people, ideas, materials, finished products, and services has expanded so rapidly that the human mind has failed to keep pace. Many of the serious political problems we face throughout the world today result from the expanding gap between the reality of interdependence and our perception of it, which lags far behind the facts. Unfortunately, there has been a congruence of two other fundamental trends that increases the complexity of the challenge of interdependence:

1. All nations are becoming increasingly dependent on exports and on the expansion of worldwide markets. The developing world has a critical need for expanding exports to generate the foreign exchange required to service the excessive debt incurred in recent years.
2. This need for further expansion of exports for debt servicing occurs when the industrialized world is just emerging from a general recession with a politically unacceptable drop in employment. Even though we are now well into a recovery stage, there is continuing political pressure for relief from foreign imports that are viewed as a primary cause of the unemployment. As a result, we see a growing threat of protectionism, which is particularly serious here in the United States. To the extent that we are unwilling to accept the exports from the developing world that are necessary to repay existing debt, we compound the financial crisis in the South, which ultimately will be our crisis, as well.

Current Challenge

We have thus experienced a fundamental change in relationships between developed and developing nations since the decolonization following World War II. Political independence in the South, paralleled by a growing economic interdependence, poses difficult problems that are an increasing threat to the economic structure on which our global society is based. This promises increasing strains in the economic relationships between the North and South that can rapidly translate into a serious worldwide crisis.

IMPACT OF ADVANCED TECHNOLOGIES

We will now review some of the advances in technology that may be anticipated over the next decade and consider their potential impacts on the economic, social, and political structures of the developing world. For this analysis, somewhat arbitrary distinctions have been made among the various areas of technological advance as they relate to the South:

- Some high-technology advances will support an improvement in global services available to the South but will continue to be controlled by the North. These advances will occur in the fields of communications, aerospace, and, to a large extent, computers and materials. Technology advances in these areas will provide benefits to the South but, because of their sophistication or for reasons of our national security, will not be transferred directly to the developing nations.
- We will support the direct transfer of other technology advances to the developing nations. These will be controlled at least in part by recipient nations and will help support economic growth and political stability.
- There is a need for programs aimed at evolving, over the longer term, a capacity to manage technology in the developing world. These programs will support development of the human resources and the domestic infrastructure to allow direct and effective application of the more sophisticated technological advances.

In each of these three areas the impacts will differ, requiring alternative approaches for dealing with the foreign policy challenge.

North-Controlled Global Services

Most of the advances in high technology, as projected by the experts, will have only an indirect or delayed impact on the developing world. Economic forces will determine, to a great extent, the basis on which this technology will be made available to the South. It is inevitable, however, that regardless of how equitable the terms, the South will consider such terms to be imposed on it to preserve the dominance of the North. At least subconsciously, this will be viewed by the South as a continuation of North-imposed "economic slavery" and "neocolonialism."

This situation calls for extreme sensitivity by the North, and the U.S. government must make every effort to minimize the negative political impact. The situation also necessitates programs that will assist the South in developing the politico-economic structure needed to participate more directly in the control over the applications of this advanced technology. Furthermore, we must understand and be responsive to the goals of these nations and their real interest in encouraging economic growth and political stability. Thus, in communications and aerospace, and largely in new materials and computers, nations of the South can become major beneficiaries of the advances projected for the next decade, although mainly in the form of services or goods provided by the North. This situation will pose a special kind of political challenge that will require sensitive and effective foreign policies.

We must additionally recognize that although the political impact from the application of high technology can be beneficial, it can also create new problems. For example, in satellite communications we have an opportunity to enhance the capacity of developing nations to exchange information and ideas. This can be most helpful in unifying a nation separated by geographical and cultural boundaries and hindered by inadequate communication services. It can also be extremely beneficial in making educational opportunities through television and radio available to remote areas that lack an educational infrastructure.

At the same time, these advances in global communications contribute to what we can refer to as the revolution of rising expectations in the developing world. In these nations the limitations that prevent accelerated social and economic development from matching the opportunities in the developed world enlarge the gap between expectation and reality. This gap has created political tensions that have played an important role in the rising discontent of developing nations. Such nations now demand economic compensation for their lack of development, which they attribute to the selfish and unfair treatment received from the North, particularly during the period of colonialism. We must be sensitive to such problems if we are to develop foreign policies that contribute to improved relations with the South.

Direct Transfer of Technology

The direct transfer of less sophisticated advances in technology and of new applications of more mature technology offers potential near-term economic benefit for the South. There are important opportunities for influencing global economic development with what we would view today as low technology, as opposed to the high-technology advances that are the primary goals of our research and development (R&D) efforts. The development of ocean transport since World War II illustrates this point.

In the early 1950s it was clear that no significant improvements in ocean transportation had occurred for over 150 years. The world shipping industry was still largely dependent on the 10,000-ton, 10-knot Liberty ship for bulk movements throughout the world. The clipper ships of the early nineteenth century sailed at higher speeds than the so-called modern ships of the 1950s, at least at times; the modern ships offered only greater schedule reliability. Furthermore, the clippers transported almost as much cargo and certainly operated at a fraction of the cost.

During that 150-year period, technological advances in land transportation, including railroads, trucking, and pipelines, conspired to bring about a substantial reduction in the real cost of moving bulk materials overland. This relative change in cost of land transport versus ocean transport influenced industrial development, and hence the economic and political growth patterns of the entire world.

In the mid-1950s companies began to push for the construction of larger ships based on new designs. This produced a complete revolution in ocean transportation throughout the 2 decades that followed. Hull forms were improved, propulsion machinery was advanced, and ship holds were modified to accommodate combination cargos. In the packaged cargo field, containerized shipping developed rapidly. The net result was a substantial reduction in the cost of ocean transportation in real terms during this period. By 1970 the cost of moving bulk material throughout the world was reduced to approximately 25 percent of the cost in 1950. During this same period, land transportation costs increased substantially in real terms. The result was, again, a major change in the pattern of global material movements. This new oceanic era generated a dramatic impact on economic growth and political relations throughout the entire world.

The Japanese, for example, built a steel industry on deep water, to accommodate the large ships that brought iron ore and other raw materials from the lowest-cost, highest-quality sources throughout the world. Contrary to the usual perception, the Japanese were *blessed* with a lack of resources. They were not faced with the problem of reconciling the difficult social and political issues inherent in discontinuing high-cost, low-quality domestic production of iron ore or coal, something that prevented the United States from becoming a beneficiary of the revolution in ocean transport. As a result, the Japanese steel industry expanded rapidly, and it soon began to reap the benefits of larger-scale operations. Continued expansion provided opportunities for introducing the newest technology, further improving its competitive position versus the rest of the world. The reduction in the cost of steel production also provided a direct benefit to the domestic automobile manufacturers. This cost advantage enhanced the competitive position of the Japanese automobile industry, which expanded rapidly, thereby creating further opportunities for introducing the newest and most efficient manufacturing techniques. In comparison, the United States steel and automobile industries are now on the ropes, operating at a serious competitive disadvantage. Both industries are fighting to protect their positions through import restrictions that, in the long run, must be counterproductive, leading us further down the road to disaster.

The initial impact of the revolution in ocean transport in the South was an acceleration in the development of resources based on world markets. At first, this offered important economic benefits. Subsequently, however, the developing nations supplying these raw materials discovered that they were subject to violent cyclical patterns of demand that created serious economic problems. Most of these operations were controlled by governments. With declining prices, production was increased to preserve the generation of revenue required to service their external obligations. This further exacerbated a difficult situation and helped bring on the disastrous drop in raw materials prices throughout the world. It compounded the economic problems not only in the developing world but also in the industrialized nations.

The implementation of this new technology, even though not of a highly sophisticated nature, has created a situation in which we have complicated the challenge of economic growth in the developing nations, increased the competition of basic industries between industrialized nations, and encouraged the development of protectionism. This situation, in turn, now creates new problems for the South.

Appropriate Technology

As we consider the kind of technology and the form of its application in the developing world, we risk an emotional response to the expression *appropriate technology*. To the developing world, this term describes the old and obsolete processes that can no longer be used effectively in the industrialized North. Transfer of this technology is viewed as another attempt by developed nations to preserve a competitive advantage over the South as a way of continuing economic dominance and control.

It is unfortunate that the term *appropriate technology* has taken on this pejorative meaning in the South, since the term properly describes technology that will contribute maximum benefits to the recipient nation. One of the challenges of our foreign policy is to develop a new expression with the same basic meaning, but one that conveys a more positive message to the developing world. In the meantime, although recognizing the danger therein, we will continue to use the present expression for lack of a more appropriate alternative.

Technological Solutions Versus Needs

For this discussion we should also establish the basic philosophical difference between the South and the North in the application of technology advances. Expressed in a somewhat simplistic way, in the South there are needs seeking solutions, whereas in the North our scientists and engineers are evolving solutions that will be seeking needs.

Although this comparison is oversimplified, it serves a purpose by distinguishing between the challenge of adopting technology advances in the developing world, as opposed to adopting them in our own. It also leads the South to solutions that in some cases we might view as low technology, but that are appropriate for the problems to be resolved. To assist in this process we will need a far greater cooperative effort between our government and the private sector, as discussed in more detail below.

Selection of Appropriate Technology

To foist on a developing nation the most sophisticated technology when it is not appropriate to the existing conditions is a tragedy and a serious disservice to that country. Although we generally measure what is appropriate largely in technical and economic terms, the South sometimes includes other important considerations in its view. For instance, tribal infighting in a West African nation may dictate what technology is provided for which region, irrespective of optimal economic efficiency. Likewise, religious beliefs in India or cultural biases in Papua New Guinea may be the decisive factors for those countries in determining what technologies they find useful or even acceptable. It is therefore important that the nations of the South select the technologies that they find appropriate for their needs. Otherwise, effective transfer and management of technology is impossible.

Development of Appropriate Technology

Unfortunately, U.S. technological advances are keyed largely to conditions that exist in the North. Whether in aerospace, telecommunications, computer design, or materials development, we tend to measure progress in terms of our own needs. We have insufficient concern for the specific needs of the developing world and the technological advances most appropriate to those needs. There is no magic formula for reversing this situation. Nevertheless, we will face even more serious problems in the future if we are not sensitive to this issue. There is clearly insufficient profit motivation to encourage private sector development in this area, and therefore the government should provide some support. Only through effective cooperation between the government and the private sector can we hope to meet this challenge.

Forms of Direct Technology Transfer

There is a great difference between the challenge associated with technology transfer on the East-West axis and that involved in North-South relations. The greater inertia and time lag in the direct application of technological advances in the developing world results from economic, social, and political considerations that significantly delay realization of direct benefits from technological advances. Of the six fields of technology to be considered in this paper, two offer potential, shorter-term benefits for the South and thus deserve more careful study. These are biotechnology and energy, which are discussed next.

Biotechnology

Developments in biotechnology hold great promise but pose potential threats, as well:

- Biotechnological advances can have a major influence in the health area, with an improvement in the quality of life. Higher survival rates and increased longevity will expand the global population and bring greater pressure on available food supplies.
- As a potential counterbalance, new advances could sharply improve food production in quality and quantity. Whether the net result of increased food supply, on the one hand, and increased requirements, on the other, is positive or negative will be influenced by government policies, including U.S.-supported efforts in these two critical areas. This also introduces the related question of birth control, which poses an even more complex challenge.
- Biotechnology can also play a role by improving the efficiency of crop production for conversion of solar energy to chemical energy. This conversion could dramatically enhance the economic potential of producing valuable energy fuels from biomass. It would assist in reducing energy costs and dependence on foreign oil imports. Energy cane, a new form of sugarcane developed for maximum lignocellulose production, is an important example of this kind of development.
- Significant opportunities in agriculture, timber, mining, and other areas of the developing world's economies are being generated by new advances in biotechnology. Our foreign policy must take into account the economic and political implications of these changes.

Energy

Developments in energy are probably influenced more significantly by economic and political factors than by technological advances. This is certainly true in the developing world. The inherent inertia in the application of energy technology, due in large part to political uncertainties, will moderate the impact of new advances in this area. Economic pressures will nevertheless continue to force application of better proven technologies appropriate for the special conditions existing in each nation of the South.

Opportunities for gain in this area include:

- energy conservation through modification of existing facilities,
- improvement in oil and gas exploration and recovery techniques, and
- adoption of processes, such as pyrolysis, for conversion of domestic sources of energy (including biomass) into useful energy forms.

All of these developments will strengthen the domestic economy and reduce the nation's dependence on oil imports, thereby improving its foreign exchange balance.

Role of the Multinational Corporation

Companies operating across national boundaries, whether U.S.-based or not, are best able to assess the economic conditions in a developing nation and thus provide the appropriate technology for direct transfer. Furthermore, the private sector largely controls the technical resources and has the capacity to manage their application throughout the world. Unfortunately, the motivation to make this technology available through investment has been greatly limited by political instability in many developing nations and, in some cases, by the lack of protection for proprietary rights.

We are trapped in a vicious circle with no obvious escape. The higher the political risk, as perceived by the multinational corporation, the greater the profit margin required to justify an investment and the shorter the payoff period. This, in turn, generates potential opposition to that investment as the developing nation becomes aware of the profit margin. It enhances the likelihood of arbitrary action against foreign owners, with expropriation of the profit, if not the property, a likely result. Arbitrary changing of rules by a host government, thereby destroying the profitability of the investment without actual expropriation of the property, is the primary risk today. This type of action accomplishes the intended result without the messy complications of compensation negotiations.

We must find a way to break this circle and create a situation in which the multinational corporation perceives the risk as manageable and is willing to accept a lower profit margin based on the long-range opportunity. To achieve this we must look to a multilateral institution, such as the World Bank, to provide assurance that the understanding of both investor and host country about the basis for the investment is equitable and will be preserved. This would provide an incentive for each side to avoid arbitrary action that might adversely affect the other party.

Such an arrangement would require some form of political risk insurance, which could also be administered by the World Bank—a goal easier to describe than to achieve. As we face continuing financial crises in developing nations, we must recognize the growing need for private-sector-controlled technology and management to support accelerated development of these nations' basic resources. It can only be hoped that these crises will become the catalysts for resolving the problem on a sound basis.

Development of the Capacity to Manage Technology

The third dimension of technology transfer is in training and education. We must give increasing consideration to the problems of developing the capacity to manage technology in the South. The political demand for technology transfers is based largely on a myth employed by the developing world to support its claim for compensation from the North. What the leaders of the South fail to realize is that if we were to pile up all of the patents and a description of all of the technologies of the entire world and place them in their hands, the net result would be a greater dependence on the industrialized world than before. The transfer of technology comes with the capacity to select, adapt, and continue improvement of technology to provide optimum results under the conditions that prevail in the developing world.

The management of technology today is largely within the purview of the multinational corporations. They not only control the technology but also have the capacity to manage it. The near-term emphasis should therefore be on creating an atmosphere in which the private sector will be encouraged to make this technology available. At the same time, we must make every reasonable effort to support the developing world in generating the capacity to manage technology by itself in the future. It is an educational process that also requires experience with actual operations, both in the host country and abroad. This calls for an intensive, cooperative effort.

To facilitate the longer-range development of a capacity to manage technology in the South, the U.S. government must play the key role. Specific actions should include:

- encouraging dialogue between the private sector and its counterpart in the developing world, aimed at establishing joint training programs;
- supporting establishment of "technology exchange centers" for specific regions in the developing world, to allow scientists and engineers from both sides to exchange views and information on new technological developments that have potential application in the region; and
- financial support for training and education, both here and abroad, in order to promote the development of the human resources required for management of technology in the South.

These steps would provide important economic gains in the South that could translate into significant economic and political gains for the North.

FOREIGN POLICY IMPLICATIONS

We have looked at a variety of ways in which technological advances can affect these developing nations. Now we turn to the bottom line: the question of what this means for foreign policy. This is perhaps the most difficult and complex question of all. Furthermore, it is a dynamic, ever-changing challenge for which there is no fixed answer, only guidelines within which foreign policy should evolve. In this we must be consistent with certain basic principles, modifying detailed policies only as required to conform to a changing environment.

Foreign Policy Principles

As a guide to this effort, we can use the following scenario, based on the outline discussed above.

First, we must anticipate a growing economic strain between the North and the South that will be dealt with in perhaps a less emotional and more thoughtful way than in the past. This does not mean, however, that the problem will be less serious, because the potential consequences could be even more disastrous. The entire structure of the global economy will be affected by the way in which we deal with these issues.

This strain will reflect the growing conflict between economic interdependence and the demands for political independence. In essence, interdependence means the loss of independence and, to some degree, a sacrifice of national sovereignty. (How can we view increasing global interdependence other than as a reduction in our options to move independently, with increasing need for an internationally coordinated effort?)

This tension will continue to grow with increasing interdependence, owing in large measure to the adoption of new technology that will further enhance our capacity to exchange people, ideas, and materials throughout the world. Somehow we must find a way to bridge the expanding gap between reality and our perception of it. Our determination to maintain political freedom in this environment must remain the paramount principle.

We must be prepared for increasing conflict on the existing debt, which will demand far greater flexibility and willingness to compromise from the North than evidenced to date. Avoidance of financial default in many of the developing nations will also require greater sensitivity to the need for expanded exports from the developing world.

Specific Foreign Policy Objectives

Specific modifications to our foreign policy will support the transfer of technology and optimize its impact on economic development. In this effort to strengthen and improve our relations with the South, we must consider the following specific objectives:

- Seek a modus vivendi for foreign corporations operating in the developing world and encourage new investments that apply the appropriate technology essential for economic growth.
- Promote and support mechanisms, such as technology exchange centers, that can assist the South in acquiring information on available technology and in developing the capacity to select intelligently and apply effectively the technology appropriate for the prevailing conditions.
- Develop policies that will encourage generation of technology appropriate for the conditions in the South and provide financial support for projects applying such technology. The Export-Import Bank should play an increasing role in this area, a role that could be particularly important in energy and biotechnology.
- Evolve policies aimed at reassuring the South that it will receive equitable treatment in the supply of goods and services produced by advanced technologies. Even though these goods and services will be

largely controlled by the North, we must provide assurance that they will be available without undue political bias.

• Support a more liberal approach to renegotiating the excessive debt burden in many developing nations. This action should recognize the practical limits of conditionality, which poses the threat of political destabilization and represents an even more dangerous risk.

• Encourage, both in the United States and in multilateral organizations, such as the General Agreement on Tariffs and Trade, a more liberal trading policy, recognizing that the developing nations must export to survive. A realistic but aggressive effort in this area will generate important economic and political dividends and will enhance the opportunities for applying new technologies.

• Strengthen support for multilateral institutions, such as the Organization of American States, which offer forums for discussions of North-South problems related to the transfer of technology. Through such institutions we can often deal better with serious issues before they reach crisis proportions. This will entail our accepting some loss of sovereignty.

CONCLUSION

In summary, the types of technology advances discussed in this symposium offer only limited benefits to the South. There will be a growing concern over the South's perception that this new technology will be used by the North to weaken further the South's relative position. Our R&D community now has little incentive to develop the less sophisticated or specialized technology more appropriate for the developing world. Whatever technology transfer takes place, the benefits of that transfer are more likely to be optimized through investments guided by market forces rather than through politically motivated government action. This probability requires consideration of steps that might be taken through multilateral institutions to improve the investment climate. A sound North-South foreign policy must be founded on an understanding of these basic issues.

The relentless nature of technological advance places us in a position much like a rafter drifting down the Colorado River. The rising canyon walls prevent an escape, and the powerful flow of water eliminates the option to return to safer waters. We know that there are rapids ahead that will change in character each day, a prospect that stirs both excitement and a fear for our well-being. Certainly, the failure to anticipate properly and deal with the potential crises ahead could lead to disaster.

Technology and East-West Relations

Bobby Inman

IT IS MY TASK to try to define the issues that will affect East-West relationships, based on papers on future technologies and on the expositions on those papers presented in the course of this symposium.

First, let me underline that the task is to discuss the East-West, not just the United States and the Soviet Union nor just the East and the United States. The first point is self-evident: the United States can play a leadership role in helping formulate the positions of the West in this East-West relationship, but it will not dictate them. As a corollary to that point, the attention we pay to the subtleties of that role and the skill displayed by the leadership in the West will to some degree determine how much flexibility and support we have as we turn to other issues. We have to recognize that in many of these issues the ability to create technology is on the growth side of the curve in both Japan and Western Europe. The potential to create new technology and the willingness to export it might also turn out to be the basis for open trade, which will be essential for the cohesiveness of our Western alliances.

With respect to the East, the existence of the Council on Mutual Economic Assistance and the control of the source of raw materials offers the Soviets some greater leverage over their allied governments, but they do not have absolute control in shaping positions about dealing with the West. There is a fair amount of flexibility as long as an approach does not threaten single-party control of the government. We have watched a range of different approaches pop up in Hungary and Rumania, and every now and again we have seen a glimmer of a different approach, at least on economic conditions, in East Germany, Czechoslovakia, and perhaps Poland. The only country that certainly will not act independently is Bulgaria, which will follow the Soviet Union like a shadow.

Since we have been inclined over the years to talk about the People's Republic of China (PRC) as part of the East when we talk about East-West, let me address that dimension first. Those who survived the "cultural revolution" and came back to leadership positions have not shared with us a great deal of detail on their experiences, but once they gathered again to themselves the reins of power, they made a major and fundamental shift in priorities, a shift from heavy industry to light industry, to a degree inconceivable in other Communist countries at present. The current PRC leaders display an understanding of the need to try to build support among the great peasantry to avoid being buffeted again by events controlled by a radical element of the Communist party.

What that shift in priorities has produced is a movement that opens the potential for a consumer-driven economy. It is by no means there now, but we may have a better chance to influence the development of this situation than to influence other situations in the Eastern bloc. Our influence comes from our decisions to make technology available and to move the PRC along the path toward a consumer economy, recognizing all the gambles that are involved when military priorities have been downgraded, but not discarded, and when the potential for a shift in a national policy back toward external use of force continues to exist. We have to recognize that if we are successful, we could find the PRC a major economic competitor as well as a major market by the year 2000, depending on decisions we make today.

With regard to the Soviet Union, which will continue to be at the heart of the East-West concern, I see no prospect of that kind of reallocation of priorities in the time frame that we are addressing in these papers. In trying to assess the different parameters of the East-West relationship before turning to the question of the role of these technologies in this relationship, the first benchmark is adaptability to change, both in the West and in the East. How adaptable will both societies be, and, particularly, how adaptable will the Soviet leadership be to the rapid pace of change which we have been told in the symposium is certain to come about?

In this country we are reasonably adept at accepting a fast pace of change. We do not always try to lead it and to shape policies for it, but on a relative scale there is not a substantial resistance to change brought about by technology development. Indeed, one of the hallmarks of U.S. dominance in technology over the last 40 years has been the relative flexibility built into our policies for institutionalization of technological change.

In the case of the current Soviet leadership we are dealing with a situation of rigidity primarily produced by the length of time in power, by age and health, and by a conservative political bureaucracy that is not concerned with offering or promoting a high degree of susceptibility to change or a high adaptability to change. When Leonid Brezhnev died and Yuri Andropov moved to power, it appeared briefly that a substantial capacity to adapt had emerged to attack at least some of the most severe structural problems (such as corruption and mismanagement), and to begin to address longer-term succession. An effort was made to move Gorbachev into some visibility, to bring Aliyev back to Moscow, and to bring Romanov down from Leningrad to Moscow. This appeared to be positioning for the potential of a generational change; whether it was a 10-year or a 20-year downward change in the age of the leadership was yet to be determined.

In dealing with external issues, at least for tactical reasons, we saw a very substantial improvement in Soviet ability to adapt to opportunity with alacrity and subtlety. Vice-President Bush went to Berlin and read a letter from President Reagan. Within 15 hours Andropov made a response. CBS had an early preview of the Scowcroft Commission report on the evening news; by the next morning Arbatov had clearance and was providing a response before the report was ever formally released. In Western Europe a major campaign was under way—a very skillful campaign that appeared to have a substantial prospect of success—to divide the North Atlantic Treaty Organization and to preclude deployment of Intermediate-range Nuclear Force missiles, a deployment that had initially originated from European concepts. But that very skillful campaign to divide the West came to an abrupt halt, probably in part because of the severity of Andropov's illness, which began in August 1983. The campaign was irreparably wounded by the incident of the Soviet shootdown of the Korean airliner.

What we have seen subsequent to Andropov's death is a retrenchment: the decision not to move down to the younger generation but rather to go with Konstantine Chernenko and the elevation of the harsh anti-U.S. rhetoric rather than the relative subtlety of the antimissile campaign in Europe. We are thus frozen into a rigidity, a lack of adaptability in that leadership that is likely to persist until the generational change comes for reason of age or health. This rigidity is likely to remain as dominant in questions of economic development and change as in those of military posture (which, of course, are intimately related in the Soviet Union's command economy). I do not take that to mean that it is a more threatening world, that we are any closer to hostilities of any variety, but simply that over the next several years there will be an even narrower prospect of any significant adaptability to change or to new proposals.

Factoring in the projected technologies, there will be some impact simply on the way one governs, as well as for relationships between countries. There are certainly major implications for trade. One question that we need to assess is what are the prospects in the East for trading partners? Was our early optimism in the late 1960s and early 1970s about the prospects for trade with the East valid, but simply went askew? It there really a substantial potential for the East as a market or as a trading partner? I think we have to look at the issue in at least three separate ways. First, I would judge that it will be a long time before the PRC really develops as a market, but the potential is certainly there. Second, Eastern Europe could possibly develop as a trading partner. As for the Soviet Union, there is not much prospect. The third part of the equation is the prospect that these emerging technologies will be used by the Eastern bloc countries primarily to enhance their military capabilities. That prospect will haunt consideration of East-West relationships throughout the application of these emerging technologies.

In trying to make assessments, let me warn of two hazards, partially repeating what I have already said. First, the rigidity of view of those who hold the reins of power in the Soviet Union should not be forgotten and one should not hold out great hope of change until there is a generational change. Second, that rigidity implies more Soviet sensitivity to things that appear to be an attack on the way the Soviets have discharged their responsibilities through 40–50 years of exercising power in their country, more sensitivity to criticisms than we might find in a younger group of leaders.

From our side, what is the greatest hazard in trying to examine the potentials for use of these technologies over the long term in our relationship with the East? I believe that the greatest hazard is "mirror imaging," the bane of repeated efforts to develop sensible policies. We decide how we would react and presume that the leadership on the other side would react in the same way. The effects of that long-standing approach are not going to make it any easier to deal with the problems ahead of us. In fact, they probably make it even worse as we look at things like technology transfer.

The foregoing brings us to a critical question: What are the fundamental bases for relationships or for hoping to improve relationships in the years ahead? We are not going to do away with the reality of an adversarial military relationship. Therefore, a fundamental part of any approach will at all times be to aim for deterrence that will sustain peaceful relationships. The second critical element will be the necessity to maintain a civil dialogue. The third element will be the need to search constantly for areas of potentially common interest that would support or encourage any kind of collaboration or ongoing dialogue.

What do I see for the near term? Today we are so focused on the question of arms control that when the Soviets leave the table in Geneva, having unfortunately built themselves a trap and then having the trap closed on them, or when they elect not to come to the Olympics, the only question one hears is, What did the United States do wrong? What should *we* change about what *we* are doing to alter that situation? We make mistakes along the way, but we are too quick to assume in every case that all of the failings, all of the causes for unfavorable decisions, must be our fault rather than situations the Soviets have created for themselves. If there is not an ongoing dialogue in Geneva, it is all the more important to look for other places and other topics for a dialogue. In this connection, one of the technologies discussed earlier in this volume by Dr. Ross in telecommunications has applicability in the near term for dealing with a very real problem of nuclear risk reduction. It may well be that there is a prospect growing out of genuine concerns about U.S. rearmament that would spur Soviet interest in efforts to reduce the possibility of escalation in any kind of conflict that occurs. The potential for technology to provide the means for more rapid and complete dialogue on critical problems should not be underestimated.

On the question of trade, I am not optimistic for the prospect in the near future of using any of the available technologies for encouraging trade. I am discouraged partly because of a tendency in successive administrations to look at trade as a political instrument. In earlier sessions of the Council on Foreign Relations there have been arguments that we cannot ignore things like the Soviet invasion of Afghanistan and that if we do not have anything else to use, we must use trade as a political weapon. We should at least understand that if we are going to get very far in looking at the implementation of new technologies in these relationships, we must first make a fundamental decision about whether or not we are going to use trade as a political weapon, using sanctions or embargoes if we see them as the best political responses to events that occur elsewhere in our relationships. However, it is important to make sure that if and when we use this approach, we understand the implications fully, particularly the effects on our friends as well as our enemies.

The problem of technology transfer continues to grow in the impact it has on the whole question of relationships. It has not yet crested. The question of military applications, however, must be seen in the light of the evidence that new indigenous technology is now being created and will continue to be created in Western Europe and in Japan. Therefore, unilateral U.S. efforts to control the flow of technology are doomed to failure. We will not be successful at all in completely blocking access. We can probably impede it for significant periods of time, but only if action is taken on a multinational basis in conjunction with our friends in the Western alliance.

For the long term, I am substantially more optimistic. When the generational change in Soviet leadership occurs, we are going to have a better-educated group of people who do not have quite the same constraining memories of the past. It could be a hazardous time if they are more arrogant about the use of conventional military power, but it may well be that they are not as frightened of new technology and what it might do and that there is a prospect for some dialogue, provided that we have laid the groundwork in our own planning to try to surface attractive offers that would generate some interesting offers in return.

On the arms control side, I would add the prospect that technology may offer nonintrusive and incrementally valuable additions in the verification area, allowing a focus on tackling problems of production and dismantling, rather than a focus on the need to look for things to count. This would be important if a high degree of verifiability is going to turn out to be the critical question in reaching agreements.

Mobility is the one exception I put to that. I do not see that the new technologies on the horizon will give a high degree of assurance in dealing with the question of mobile weapons systems, but maybe I am being overly pessimistic.

I think that in nuclear risk reduction, particularly if we have an earlier start, there may be additional prospects, common interests that we will find because of questions of nuclear proliferation in the Third

World countries and perhaps, by that point, some shared experiences and mutual concerns about terrorism. This capability may be enhanced with the application of advanced telecommunications technologies in promoting real-time information exchange or in reducing uncertainty. The planned U.S. manned space station could possibly contribute to stability in this area by providing the potential for use in some kind of a joint observation capability for reducing uncertainty when there is a debate or disagreement about what other sensors have provided. That might well have some substantial appeal.

The trade side will, to a large degree, be influenced by the relative judgments about the military balance. Clearly, if we are to develop any substantial improvement on the trade side, we will have to be willing to transfer technology. Here again, there may be some areas in which we will find technology transfer to be in our interest, such as trying to move toward standards in the telecommunications area. Participants in this symposium have addressed the constraints on domestic production, but this could be an area in which (because there is enough long-term common interest in the improvements in trade that substantial enhancements in telecommunications would provide) East and West might cooperate, though we might to some degree be working against some North-South elements.

We might find some potential for joint agreements for space exploration, particularly with the space telescope if it offers the potential described by Hans Mark.

On the question of whether it is conceivable to share technology in the strategic defense initiatives, I have heard what was said in the public speeches about our willingness to share prospective success in those areas. I must say that, based on my experience over the past 31 years, I doubt that we would ever produce agreement in the Department of Defense to share those technologies. Although a strong civilian leadership might lead us there, I remain somewhat skeptical.

Materials science and energy I leave to my other colleagues to speculate on. I have some difficulty seeing in either case where these new technologies offer potential for improving relationships (either through trade or through political agreements, or arms control agreements over the long term). However, the biotechnology area, I think offers some prospects, and let me express here a final, wistful hope. I have discussed above the changes in priorities in the PRC and my conviction that I do not see over the next 15 years any prospect of similar changes in the Soviet Union. The question, if one is not following events in the Soviet Union closely, must be, Why would I reach those conclusions? Nikita Khrushchev brought about fundamental changes within the Communist party and in the routes to power by doing away with terror as a weapon to hold the party in line. Terror could still be used against the average citizen, but after 1956 a good member of the party who did not get too deeply involved in corruption or did not get involved in foreign espionage activities did not have to worry about the knock on the door in the middle of the night. The bureaucracies began to form and work toward building a constituency that helped party members in the process of moving to become candidate members of the Central Committee, then to full Central Committee membership, and then to candidate members of the Politburo. Those who are moving up owe some response to patronage from those who are already there, but they also owe their future success to setting priorities and then fulfilling them. There are some rare exceptions. That is why I look to Gorbachev as the hope. He has to be the ablest politician now visible on the Soviet scene. Having presided over three agricultural failures and having escaped any of the blame, he clearly is a very competent politician.

Romanov proved to be a skillful administrator in Lenigrad. Aliyev gives cause to worry. I am still not sure whether Andropov brought him to Moscow to groom him for power or to be able to watch him more closely, but regardless, he would certainly be a very forceful leader. The new leadership might be interested in escaping the past cycles of agricultural failures. They could offer through access to biotechnological successes a substantial enhancement in the quality of goods and services available at affordable prices to the broad Soviet population. I think there is a glimmer that they might start some reevaluation of priorities and allocations. Without this sort of attitudinal-generational change, I see no other prospect of a move away from a state-ordered economy that continues down the same spending paths on which it is now going with the same allocations and priorities. Therefore, the likelihood is that the Soviets will not be interested in moving into any substantial trading relationship with the West, at least in the near years.

Biographical Sketches

ALLEN E. PUCKETT *(Chairman)* is Chairman of the Board and Chief Executive Officer of the Hughes Aircraft Company. He has been in key management positions with the company for nearly three decades. Prior to joining Hughes, Dr. Puckett was Research Associate in aerodynamics at the California Institute of Technology, Technical Consultant at the U.S. Army Ordnance Aberdeen Proving Ground, and Chief of the Wind Tunnel Section for the California Institute of Technology's Jet Propulsion Laboratory. He has served on numerous industry and government committees, including the Defense Science Board and the Aerospace Industries Association. Dr. Puckett is a member of the National Academy of Sciences and the National Academy of Engineering and is the author of several technical papers on high-speed aerodynamics.

ARDEN L. BEMENT, JR., was appointed Vice President, Technical Resources, TRW, Inc., in January 1981. In this position he identifies and evaluates emerging technologies and recommends product, material, and process development projects. Dr. Bement began his professional career in 1954 as Research Metallurgist and Reactor Project Engineer with General Electric Company at the Hanford Atomic Products Operation. He joined Battelle Memorial Institute as Manager of the metallurgy research department in 1965 and 3 years later became Manager of the fuels and materials department. He joined the faculty of MIT as Professor of Nuclear Materials in 1970. From 1974 to 1976 he served as a member of the U.S.-U.S.S.R. Bilateral Exchange Program in Magnetohydrodynamics and was the organizer and principal investigator of the MIT Fusion Technology Program. Dr. Bement has edited three books and authored over 90 articles on materials science, energy, and defense technology. He is a fellow of the American Nuclear Society, the American Society for Metals, and the Institute of Chemists. In addition, he is a member of the National Academy of Engineering and the American Institute for Mining.

J. FRED BUCY is President of Texas Instruments Incorporated. He received his bachelor's degree in physics in 1951 from Texas Tech University and his master's degree in physics from the University of Texas, Austin, in 1953. Upon completion of his studies, Mr. Bucy joined the Central Research Laboratories at Texas Instruments where he did research in instrumentation for oil exploration. He was promoted to Corporate Vice President (1963) and then elected Executive Vice President (1972). Mr. Bucy was elected to the Board of Directors of Texas Instruments in 1974 and was named Chief Operating Officer in 1975. He was elected to his current position in 1976. Mr. Bucy holds membership in the Council on Foreign Relations, the Technology Assessment Advisory Council of the Office of Technology Assessment of the U.S. Congress, Comptroller General's Consultant Panel, Council of the Woodrow Wilson Center, Conference Board, Presidential Commission for a National Agenda for the Eighties, and the Defense Science Board, among others.

RICHARD N. COOPER is Maurits C. Boas Professor of International Economics at Harvard University. He received his bachelor's degree from Oberlin College in 1956 and his Ph.D. from Harvard in 1962. From 1961 to 1963, he was Senior Staff Economist with the Council on Economic Advisors. Dr. Cooper served as Deputy Assistant Secretary of State for International Monetary Affairs from 1965 to 1966 and was Under Secretary of State for Economic Affairs from 1977 to 1981. He became Professor of Economics at Harvard in 1981. Dr. Cooper is a member of the Council on Foreign Relations and the Trilateral Commission, as well as a fellow of the American Academy of Arts and Sciences, and is the author of numerous articles on economic policy.

EDWARD A. FRIEMAN is Executive Vice President of Science Applications, Inc., in La Jolla, California. He received his bachelor's degree in engineering from Columbia University and his master's and doctorate degrees in physics from the Polytechnic Institute of Brooklyn. Following completion of his graduate studies, Dr. Frieman served as Research Assistant at Princeton University. Subsequently, he held the positions of Professor of Astrophysical Science and Deputy Director of the Plasma Physics Laboratory at Princeton. From 1979 to 1981, he was Director of Energy Research for the U.S. Department of Energy and also served as the principal Science Advisor to the Secretary of Energy. He joined Science Applications, Inc., in 1981. Dr. Frieman is a member of the National Academy of Sciences and the Defense Science Board. He is Chairman of the White House Science Council as well as Chairman of the Planning and Steering Advisory Group of the Advanced Technology Panel for the Vice Chief of Naval Operations.

RALPH W. F. HARDY is President, BioTechnica International and former Director of Life Sciences for E. I. du Pont de Nemours & Co., Inc. He earned his bachelor's degree from the University of Toronto and his master's and doctorate degrees in biochemistry from the University of Wisconsin. Dr. Hardy joined Dupont in 1960 as Research Biochemist and was promoted to Research Supervisor of Plant Sciences in 1967. He became Associate Director of Life Sciences in 1974 and served in that position until he was appointed Director of Life Sciences in 1979. He is a member of the American Society of Plant Physiologists, the American Chemical Society, and the American Society for Microbiology. His research interests include plant biology and biochemistry, including nitrogen inputs into major crops and carbon input, nitrogen fixation, and photosynthesis.

ANN L. HOLLICK is currently Director of the Office of International Trade with the U.S. Department of State and a former National Science Foundation Visiting Professor at the Massachusetts Institute of Technology where she had a joint appointment with the Political Science Department and the Center for International Studies. She was graduated from the University of California at Berkeley in 1963 with a bachelor's degree in English. In 1971 she received her doctorate degree in political science from Johns Hopkins University. Dr. Hollick became Assistant Professor of Political Science at the Johns Hopkins University School of Advanced International Studies in 1972 and was promoted to Associate Professor in 1975. Between 1979 and 1983, she served in two positions with the U.S. Department of State. As Director of the Planning Staff for the Bureau of Oceans, Environment, and Scientific Affairs, she was responsible for developing planning studies on oceans and the environment; as Director of the Office of International Commodities for the Economic and Commercial Bureau she negotiated international commodity agreements, supervised foreign policy aspects of U.S. strategic materials policy, and guided foreign policy on seabed mining and Antarctic minerals. Dr. Hollick is a member of the Council on Foreign Relations and the Woods Hole Oceanographic Institution.

BOBBY R. INMAN is President, Chief Executive Officer, and Chairman of the Board of Directors of the Microelectronics and Computer Technology Corporation. He received his bachelor's degree from the University of

Texas at Austin in 1950 and entered the naval reserve the following year. He was commissioned as an Ensign in 1952. Admiral Inman's early career included a variety of assignments in Naval intelligence, including tours as the Chief of Naval Operation's Intelligence Briefer, and Assistant Naval Attache, Stockholm, Sweden. He was graduated from the National War College in 1972. He served as Assistant Chief of Staff for Intelligence to the Commander in Chief, U.S. Pacific Fleet, 1973–1974; as Director of Naval Intelligence, 1974–1976; and as Vice Director, Plans, Operations and Support of the Defense Intelligence Agency, 1976–1977. He was appointed Director of the National Security Agency in July 1977, where he served until March 1981. Coincident with his assignment as the Deputy Director of the Central Intelligence Agency, he was promoted to the rank of Admiral, the first Naval Intelligence Specialist to attain four-star rank. He retired with the rank of Admiral in July 1982. Admiral Inman serves as a member of the Defense Science Board and as a member of the Board of Directors of the Dravo Corporation, Science Applications, Inc., and the Western Union Corporation. He is also a Senior Fellow at the Hoover Institution of War, Peace and Revolution at Stanford University.

HANS MARK is Chancellor of the University of Texas System, Austin, and former Deputy Administrator of the National Aeronautics and Space Administration. He previously served as Secretary of the Air Force from 1979 to 1981 and as Under Secretary of the Air Force since 1977. He was born in Germany in 1929 and came to the United States in 1940, becoming a citizen in 1945. He received his bachelor's degree from the University of California at Berkeley in 1951 and his doctorate degree in physics from the Massachusetts Institute of Technology in 1954. Between 1954 and 1969, Dr. Mark served as Acting Head of the Neutron Physics Group, Laboratory for Nuclear Science at MIT; Research Physicist at the University of California at Berkeley's Laurence Radiation Laboratory in Livermore; Assistant Professor of Physics at MIT; Chairman of the University of California at Berkeley's Department of Nuclear Engineering and Administrator of the Berkeley Research Reactor. In February 1969, he became Director of NASA's Ames Research Center where he managed the center's research and applications efforts in aeronautics, space science, life science, and space technology. Dr. Mark is a member of the National Academy of Engineering and is a fellow of the American Physical Society and the American Institute of Aeronautics and Astronautics.

SIMON RAMO is co-founder and currently Director of TRW, Inc., formerly the Ramo-Wooldridge Corporation. Dr. Ramo was educated in electrical engineering and physics, receiving his Ph.D. from the California Institute of Technology in 1936. He is a founding member of the National

Academy of Engineering, a member of the National Academy of Sciences, the American Philosophical Society, and the American Academy of Arts and Sciences. He was chairman of the President's Committee on Science and Technology under President Ford. Included among his many awards are the National Medal of Science in 1979 and the Presidential Medal of Freedom in 1983.

C. W. ROBINSON is currently Chairman of the Energy Transition Corporation. He received his bachelor's degree in international economics from the University of California at Berkeley in 1941 and his MBA from Stanford University Graduate School of Business in 1947. Mr. Robinson's career spans industry, government service, and investment banking. From 1964 to 1974, he was President of Marcona Corporation in San Francisco. In 1974, he was appointed Under Secretary of State. While at the State Department, Mr. Robinson negotiated the Soviet Grain agreement, participated in the development of international energy and nuclear proliferation policies, and urged productive communications between industry and developing countries. He joined Kuhn Loeb & Co., Inc., as Senior Managing Director in 1977 and became Vice Chairman of the Board of Blyth Eastman Dillon and Co., Inc., in 1978. Mr. Robinson is currently founding Chairman of the ASEAN-US Business Council, a member of the Board and of the Executive Committee of the Trilateral Commission, and a member of the Council on Foreign Relations.

IAN M. ROSS is President of AT&T Bell Laboratories. A native of England, Dr. Ross received his B.S. degree from Gonville Caius College of Cambridge University in 1948. He received his M.A. and Ph.D. degrees from Cambridge in electrical engineering in 1952. Dr. Ross began his career at Bell Labs in 1952. He became Managing Director of Bellcom, Inc., a Bell System subsidiary which provided systems engineering support for the Apollo manned space flight program, in 1964 and became President in 1968. Dr. Ross returned to Bell Labs in 1971. Since then, he has served as Executive Director, Network Planning Division; Vice President, Network Planning and Customer Services; and Executive Vice President, Systems Engineering and Development. He became President of Bell Labs in April 1979. Dr. Ross has accumulated 17 patents and published numerous papers and articles during his 30 years at Bell Labs and at Bellcom, Inc. He is a member of the Board of Directors of AT&T Bell Labs, AT&T International, Inc., AT&T Technologies, Inc., and Sandia Labs. He is a member of the National Academy of Engineering and the National Academy of Sciences and is a fellow of the Institute of Electrical and Electronics Engineers and the American Academy of Arts and Sciences.

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