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CONTENTS

AN OVERVIEW OF ELECTRIC ENERGY RESEARCH

AN OVERVIEW OF ELECTRIC ENERGY RESEARCH

Craig S. Tedmon, Jr.
General Electric Research and Development Center
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This talk is entitled "An Overview of Electric Energy Research," but that's not what I'm really going to talk about. You people know much more about what's happening in electric systems research than I do. My message will not be about technological changes, but about a change in the way we should look at the role of technology. My theme is that we have moved from an age of technology-driven markets to an age of market-driven technology.

I'll develop that theme by first looking at the way things were; then I'll look at the changes that have occurred, try to identify some of the implications of those changes on technology, and end by looking at the implications of those changes for the way bodies such as this committee might think about research and development.

The situation we face today is very different from the past history of the industry when technology created waves of new uses--from Edison's light bulbs to air conditioning--and steadily reduced the cost of generating electricity, and when demand predictably grew in response to new ways to use electricity in homes, offices, and factories, and to falling electricity prices. Technology was the driving force.

Today, new technologies are coming along faster than ever. But today, they are mainly technologies for transforming information, not energy. Today, they're driving the creation of information utilities and information equipment suppliers in much the same way that the electrical revolution of the past century created the electrical utilities and manufacturers.

But from the point of view of the electrical industries, these information and electronic revolutions are far less dramatic than the advent of light bulbs, refrigerators, and air conditioning. Today's new technology does not add much load. That's obviously true for the new technologies in the home--personal computers and VCRs, for example. It's less obvious--but just as true--for the automation, information, and communication technology that's going into the factory.

The data in Table 1, assembled by General Electric's (GE) Electric Utility Systems Engineering Department, provide a snapshot of U.S. industry in 1980 in terms of kilowatt hours of electricity used for

TABLE 1 1980 Industrial Electrical Energy Usage

Industry	KWH / Dollar of Value Added
Primary metals	3.46
Chemicals	2.05
Paper	2.05
Petroleum and coal	1.60
Stone, clay, and glass	1.29
Textile mill products	1.18
Food and related products	0.57
Electrical and electronic products	0.36
Instruments	0.18

each dollar of value added by the industry to its product. But more important, this provides a signpost for the future. If you look at the heavy users of electricity per dollar of value added, they're mainly in the mature, slowly growing, or even declining industries--primary metals; paper; petroleum and coal; and stone, clay,and glass, for example. By contrast, today's fastest growing industries--electronic equipment and instruments, for example--are near the bottom of the energy intensity list. It takes less than one-fifteenth as many kilowatts to add a dollar to the value of a computer as it takes to add a dollar to the value of an ingot of steel.

But how about all that automated equipment in the factories? Won't they be using a lot of electricity? Again, not enough to make much difference. Robots work at lower light levels than humans--and that decrease in lighting load alone can offset any increase in electricity demand caused by the robot.

How about supply-side technology? Again, it will not be a driving force. The so-called exotic energy sources--sun, wind, tides, and the rest--have been tried. None looks like it will be cost competitive except in a few special situations. In my view the most successful experiment to come out of the energy crisis era is the integrated gasification combined cycle plant at Coolwater in California. It was built on time and within its budget, and is working well enough to provide good evidence that electricity produced by an integrated gasification combined cycle plant--or IGCC--can be competitive.

If technology isn't driving things, what is? I'm no expert in load forecasting, but here's how some of the experts tell me they do it. They break the load into three components: residential, commercial, and industrial. They make detailed models of load in each of these areas, and it essentially turns out that the load in each one corresponds closely to one major variable. Thus, the growth rate of residential load is primarily determined by the rate of household formation; the commercial load follows the total amount of floor space in commercial use; and the industrial load--in spite of those substantial differences in the energy intensiveness of industries I mentioned earlier--swings with the gross national product (GNP). The effect of energy conservation and changing industrial energy intensity is to effectively reduce the proportionality between changes in GNP growth rate and the rate of energy usage.

So if you know the rates of household formation, commercial floor space growth, and GNP growth, you can make a good estimate of load growth. Projections based on these kinds of models give an expected load growth of about 2 to 2-1/2 percent per year.

That kind of load growth decreases the incentive for utilities to be venturesome in adding technically innovative new capacity. It increases the incentive for utilities to upgrade existing capacity.

The extent to which utilities upgrade, rebuild, and otherwise stretch out the life of their existing equipment adds further uncertainty about future markets. And the greater the uncertainty, the harder the electrical manufacturing industry finds it to justify and support the rapid and costly development of radically new technology.

Technology opportunities do exist today, and in many cases they are very significant. I've mentioned that the Coolwater project provides impressive evidence of the viability of coal-fired combined cycle plants. In transmission, high voltage direct current (HVDC) technology has certainly arrived, and there's nothing to prevent the industry from moving the power of Manitoba down to Minnesota, or replacing Florida oil with Georgia coal. Our engineers have taken a serious look at moving the oil of Alaska's North Slope to Los Angeles in the form of electricity, and that's perfectly feasible. As one of them put it, technically and economically there's nothing to stop you from moving power between any two points on the North American continent.

These opportunities are bringing forth some very interesting engineering challenges--from interrupting a dc current of many thousand amperes, through taking advantage of rapid improvement in fiber optics and in thyristors, to developing microprocessor logic for complex controls.

There are examples in distribution technology, too. For example, amorphous metals are a major materials breakthrough. To take advantage of them requires a whole new look at the design of distribution transformers, and a comprehensive systems understanding of the value of losses in the distribution network.

So it's not a question of technology opportunities not existing. It's a question of the market driving forces not being in place. And that brings me back to the theme of these remarks. We have entered an era of market-driven technology rather than technology-driven markets.

I want to make a very important distinction here between market driving forces and economic driving forces. You can make a very nice economic argument in favor of each of the technologies I've mentioned. You can make the economic argument that utilities are better off with coal-fired combined cycle plants, no matter what happens to load growth and oil prices in the years ahead. You can prove the economic viability of moving nuclear power via HVDC from Phoenix to Los Angeles, or coal-fired power via HVDC from Ohio to Oklahoma. You can demonstrate the economic viability of replacing every distribution transformer in the nation with an amorphous metal transformer.

But economic feasibility isn't market feasibility. To stimulate a market, you have to do more than show that it will pay off somewhere down the road. You also have to show the route to get from here to there. And you have to show that route is prudent--that the market risks are manageable.

The economically feasible things will happen only if the market forces are right. And market forces are influenced by barriers. Right now those barriers are high--barriers of slow load growth, high costs, uncertain financial health, uncertainties about fuel cost and availability, environmental issues, reliability questions, and the regulatory environment. From the point of view of the manufacturers, the barriers are excess manufacturing capacity that keeps profit margins low, and strong foreign competition, aided by a strong dollar and foreign government protectionist trade policies and subsidies. All of these do not invalidate the long-run economic arguments favorable to new technology. But they do put high barriers in the way of the development of markets for those technologies. And slowing down the rate of market growth keeps the barriers high, and vice versa. For example, a small market for amorphous metal transformers might keep the price of amorphous metal high, which might in turn keep the market down, and so on.

So that's the nature of market-driven technology. It offers less glamorous vistas to R&D than the technology-driven era that preceded it. But rather than looking back nostalgically on that era, we should be adjusting our sights to aim at today's market needs. I'll conclude by suggesting three main rationales for systems research in the market-driven technology era.

The first is promoting the electricity-related applications of the fast-moving technologies being developed primarily for use in other areas. For example, computer and information technology is moving very rapidly. But in many of its potential applications to electricity, such as modeling and analyzing very complex systems, the near-term payoff for private industry is marginal. Government has a role in exploring the advanced uses and applications of this technology, perhaps by sponsoring research on challenging problems like the analysis of a national electrical grid--problems that may not have much practical significance now, but that might stimulate the development of more powerful methods of modeling and analyzing electric power systems.

Those methods may become increasingly practical as today's most powerful computers become less expensive. Those cost reductions and increases in computer power are coming along faster than ever today. Projections based on the characteristics of supercomputers in the development stage today indicate that the speed of the fastest supercomputers will go up even faster in the future than it has in the past. Yesterday's supercomputer is turning into today's mainframe, and today's mainframe is turning into tomorrow's personal computer. Competition is driving down the cost of today's models while computer scientists are moving on to explore entirely new types, based, for example, on fully parallel computer architectures that are especially designed for network problems. Perhaps this kind of capability will become useful in the modeling and real-time control of power systems. In any case the potential of new computer architectures should continue to inspire fundamental research.

A second main area appropriate for publicly sponsored research in a market-driven era is knowledge essential for the public good, but with a payoff too diffuse or too uncertain for private companies to do the research. Research on the biological effects of electric and magnetic fields is a good example. The research should be done, and it should be done under sponsorship of an organization that not only takes an objective view but also will be perceived as taking an objective view. The government is clearly the appropriate sponsor for this kind of research.

Finally, there's the area of reliability. In part it presents new versions of familiar problems. When new types of equipment go onto a system, they may produce some unpredicted effects. Today some of the main equipment impacts come from the electronic wave-shaping equipment used in new types of variable-speed drives, electronically commutated motors, and other new types of electronically controlled rotating machinery. This introduces new harmonics to the system--another chapter in a continuing story. The analysis of the potential effects of these harmonics is a legitimate area for government-sponsored research.

But a more interesting and newer opportunity for using technology to improve reliability comes from the technologies of artificial intelligence and expert systems. They're new and different ways of using computer power by writing computer programs that capture the knowledge and skill of human experts in software. In principle they make possible teamwork between a person and a computer, rather than merely surrendering decision-making capability or system-control responsibility to a computer. Might such capabilities be useful in such areas as systems design, or the control and monitoring of power plants?

I'm not recommending these specific fields for research. That's really the business of your panel, and you know how to do it much better than I do. My message today has been focused on attitudes toward R&D. To sum up that message, we are now in an era of market-driven technology. We could regret that, and look back with longing upon the golden age. But that, I believe, would be a mistake. In the era of market-driven technology, R&D still has an important role. It can provide a national view that transcends the narrow view of the participants in the business. It's still essential for such ongoing concerns as reliability. And, finally, it can keep the electric utility and electrical manufacturing industries receptive to the truly revolutionary technologies that retain, even in an age of market-driven technology, the capability to change the world.

GROUP 1

SYSTEMS TECHNOLOGY

MATERIALS RESEARCH*

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ABSTRACT

This presentation on materials will concentrate on dielectric and electrical insulation materials and the directions and needs for research and development. Some examples will also be given on amorphous metals and metal oxide varistor developments that can have significant impact on future equipment designs.

Under the existing situation of the limited load growth projections in the utility industry, no single manufacturer of power equipment can justify a broad-based, fundamental, and coordinated research program to develop electrical insulation systems to meet long-term needs. The trend is, therefore, toward a weakening of the U.S. competitive position and the potential for a lack of availability of key products from domestic sources needed by the utility industry.

Dielectric materials are the basic building blocks for all equipment and function, in addition to the electrical insulation function, as mechanical supports and heat transfer media. This multifunctional role of the electrical insulation system imposes significant constraints on the selection of materials for efficient and reliable electrical equipment.

In the future it is likely that more emphasis will be given to underground and encapsulated transmission and distribution systems, as a result of increased opposition to overhead and exposed equipment, for environmental and safety reasons as well as reduced access to rightsof-way. To achieve compactness and to maintain high reliability, the requirements of the electrical insulation system for transmission and distribution equipment will, therefore, be more demanding.

*Research sponsored by the Department of Energy, Electric Energy Systems Division, for Martin Marietta Energy Systems, Inc., under Contract No. DE-AC05-84OR21400.

To meet the challenges for the future, it is necessary to develop better understanding and knowledge of the fundamental behavior of dielectric materials. This includes studies of individual materials, material composites and insulation systems, interfacial phenomena, and the factors influencing aging of materials and systems including multi-factor aging and environmental effects.

Sophisticated analytical and data acquisition techniques, made possible by advances in electronics and optics, are becoming more affordable. This provides an opportunity to obtain a better understanding of fundamental material characteristics and system behavior and interactions.

The Division of Electric Energy Systems of the U.S. Department of Energy has formulated a program that will give national focus and direction to the research and development (R&D) of advanced dielectric materials and concepts for use in future electric power transmission, distribution, and station equipment. This program is intended to further the fundamental understanding of dielectric materials and to provide a data base for the development and application of these materials.

THE DECLINE IN DOMESTIC R&D RESOURCES, ESPECIALLY IN MANUFACTURING COMPANIES AND THE INCREASING DEPENDENCE OF OUR UTILITY INDUSTRY ON OFF-SHORE TECHNOLOGY, ARE SERIOUS THREATS TO THE HEALTH AND SECURITY OF OUR NATION.

EXAMPLES:

- NO NEW MAJOR GENERATION ORDERED IN THE LAST SEVEN YEARS.
  --R&D ON GENERATION VIRTUALLY CLOSED DOWN.

- EFFECTIVELY NO DOMESTIC EHV CIRCUIT BREAKER MANUFACTURERS. RESEARCH VIRTUALLY CLOSED DOWN FOR THE LAST FIVE YEARS.

- NO DOMESTIC SUPPLIER OF GAS INSULATED SUBSTATIONS.

- MEDIUM AND LARGE TRANSFORMERS: WILL THE U.S. HAVE A DOMESTIC SUPPLIER BY 1990?

Figure 1 The present situation and trends in the U.S. power equipment industry.

- SIGNIFICANT EROSION IN TECHNOLOGY AND KNOW-HOW

- DIFFICULT TO ATTRACT YOUNG EXPERTS TO INDUSTRY

- TOTAL RELIANCE ON OFF-SHORE TECHNOLOGY AND SUPPLY

Figure 2 Consequences.

MATERIALS FORM THE BASIC BUILDING BLOCKS IN ALL EQUIPMENTS

- ELECTRICAL CONDUCTORS
- MECHANICAL SUPPORT
- ELECTRICAL INSULATION
- HEAT TRANSFER MEDIA

Figure 3 Importance of materials research for the electrical industry.

IN ORDER TO PROVIDE THE PROPER FUNCTION, MATERIALS MUST MEET EQUIPMENT OPERATING SPECIFICATIONS

- ELECTRICAL
- MECHANICAL
- THERMAL
- RELIABILITY
- ENVIRONMENTAL
- COST

Figure 4

- ENVIRONMENTAL OPPOSITION AND CONCERNS
- HEALTH AND SAFETY CONSIDERATION
- LIMITED RIGHTS-OF-WAY
- INCREASING URBAN LOADS
- HIGHER EFFICIENCY
- IMPROVED RELIABILITY

Figure 5 Determinators.

PCB'S; ASBESTOS; FLAMMABILITY OF OILS AND POLYMERS; PROCESSING INVOLVING SOLVENTS; OPPOSITION TO SITING OF OVERHEAD LINES.

Figure 6 Environmental and safety.

- MORE EMPHASIS ON UNDERGROUND AND ENCAPSULATED SYSTEMS
- HIGHER ELECTRICAL STRESS DESIGNS
- RETROFIT IN EXISTING FACILITIES WITH HIGHER CAPACITY

Figure 7 Likely solutions.

- IMPROVED OR OPTIMIZED EFFICIENCY
  - -- MINIMUM INSULATION THICKNESS
  - -- LOWER LOSSES
- DEVELOP HIGHER VOLTAGE SYSTEMS
- ADEQUATE RELIABILITY UNDER APPLICATION CONDITIONS
- SATISFACTORY PERFORMANCE AT MINIMUM COST
- AVAILABILITY OF ENVIRONMENTALLY ACCEPTABLE MATERIALS AT REASONABLE COST

Figure 8 Objectives of material application.

- IMPROVED DESIGNS
- IMPROVED MATERIALS
- IMPROVED TESTING TECHNIQUES
- ENHANCED SYSTEM RELIABILITY AND PROTECTION
- POWER SYSTEM MONITORING AND DIAGNOSTICS

Figure 9 Direction to these objectives.

- REDUCTION IN BASIC INSULATION LEVEL (BIL)
- DIELECTRIC ARRANGEMENT AND DIELECTRIC CONSTANT CONTROL
- ELECTRICAL STRESS CONTROL
- ADVANCED MATERIALS

Figure 10 Design.

- IMPROVED ELECTRICAL CHARACTERISTICS
- IMPROVED MECHANICAL CHARACTERISTICS
- BETTER THERMAL STABILITY
- MATERIAL COMBINATIONS
- IMPROVEMENT IN PROCESSING AND HANDLING
- REDUCTION IN DEFECTS
- RESISTANCE TO ENVIRONMENTAL EFFECTS, TRACKING, AND EROSION
- ENVIRONMENTALLY ACCEPTABLE

Figure 11 Improved dielectric strength of materials.

- ACCELERATED LIFE TEST (AGING)
  - -- THERMO-CHEMICAL
  - -- MECHANICAL EFFECTS
  - -- VOLTAGE EFFECTS
  - -- ENVIRONMENTAL EFFECTS
- MULTIFACTOR EFFECTS ON MATERIAL LIFE
- SHORT-TERM TESTS TO DEMONSTRATE LONG-TERM RELIABILITY
- NONDESTRUCTIVE TEST TECHNIQUES
- FAULT DETECTION AND LOCATION
- NEW INSULATION SYSTEMS
- DETERIORATION IN SERVICE

Figure 12 Improved testing techniques.

- ADVANCED PROTECTION TECHNOLOGY - ZnO
- IMPROVED FAST TRANSIENT RESPONSE
  - -- PROTECTION EQUIPMENT
  - -- INSULATION SYSTEM
- IMPROVED DC CHARACTERISTICS
  - -- BETTER UNDERSTANDING OF CHARGING PHENOMENA OF/IN DIELECTRICS AND INTERFACES

Figure 13 Enhanced system reliability and protection.

- NONDESTRUCTIVE ON-LINE TESTING
- PREDICT EQUIPMENT LIFE FROM HISTORY
- "SMART" APPROACH, I.E., COMPUTER BASED DIAGNOSTICS WITH ARTIFICIAL INTELLIGENCE

Figure 14 Power system monitoring and diagnostics.

- UNDERSTANDING MECHANISMS
  - -- GAS, SOLIDS, LIQUIDS, AND MATERIAL COMBINATIONS
- UNDERSTAND INTERFACIAL PHENOMENA
- UNDERSTAND AGING PHENOMENA
- UNDERSTAND CHARGING PHENOMENA (ELECTRIFICATION)

Figure 15 To meet these objectives, the mechanisms which govern material behavior must be understood.

LOWER MANHATTAN (SOUTH OF CHAMBERS STREET)...............500,000

A CONSTRUCTION BOOM NEAR WALL STREET IS ADDING ABOUT 15,000,000 SQUARE FEET OF OFFICE SPACE--EQUIVALENT TO THE DOWNTOWN MIAMI AREA, EXPECTED TO ACCOMMODATE OVER 50,000 WORKERS. THIS IS TO BE COMPLETED IN A FEW YEARS, AND WILL BE A 10 PERCENT INCREASE IN THE AREA'S DAYTIME POPULATION. (WSJ. 10.15.84)

Figure 16
Source: Electric Power Research Institute

NEW YORK CITY	3,000,000
LOS ANGELES	1,500,000
CHICAGO	1,300,000
HOUSTON	950,000
PHILADELPHIA	700,000
DALLAS	600,000
WASHINGTON, D.C.	600,000

Figure 17 Daytime worker population.

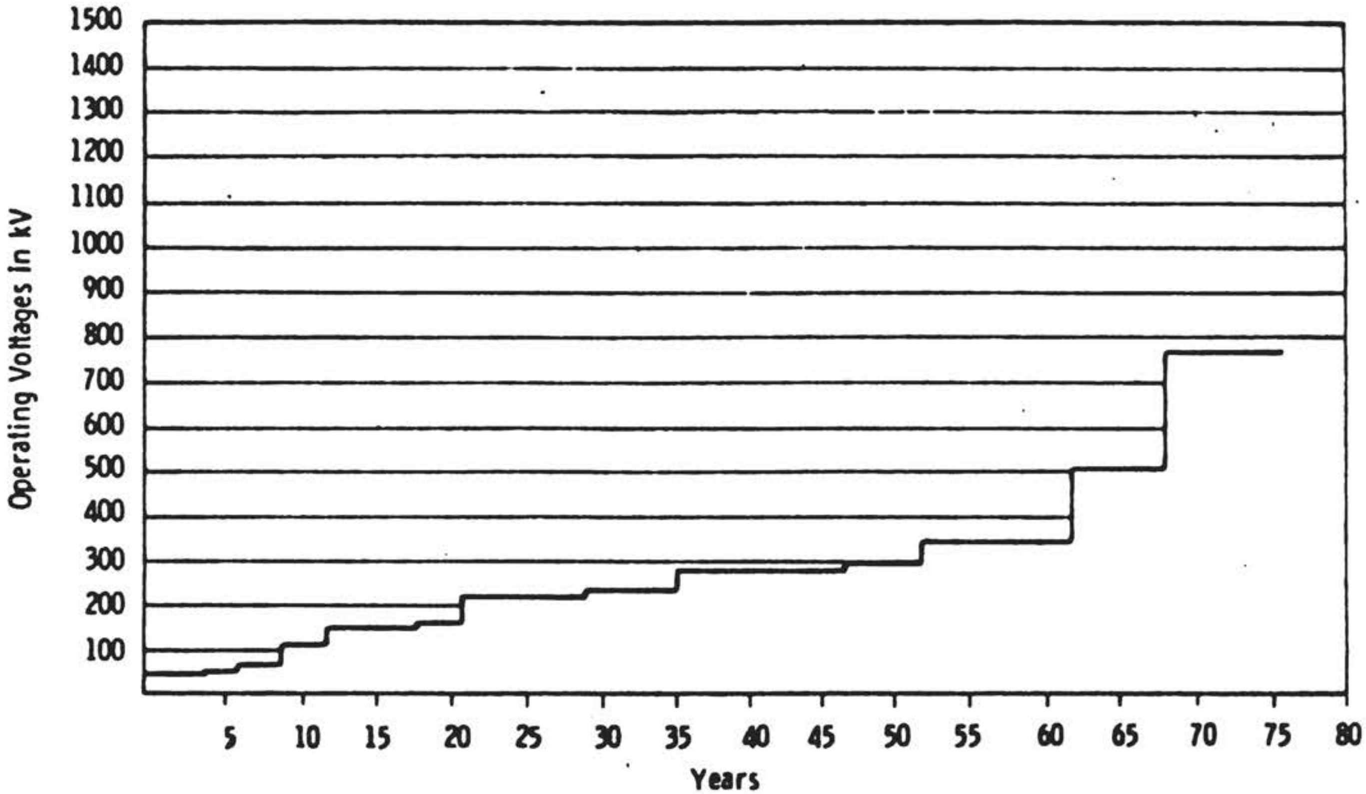

Figure 18 Growth in electric power system voltages since 1900.
Source: T. W. Dakin, IEEE Trans. Electrical Insulation, Vol. EI-13, No. 4, 1978.

DURING 1980 U.S. CONSUMPTION OF ELECTRICITY WAS APPROXIMATELY 2.5 TRILLION KWh

WITH OVER 40 MILLION POLE-MOUNTED DISTRIBUTION TRANSFORMERS IN USE THEIR TOTAL ANNUAL CORE LOSSES ARE APPROXIMATELY 35 BILLION KWh

REPLACEMENT BY AMORPHOUS-CORED TRANSFORMERS COULD MEAN AN ANNUAL SAVING OF 2W3 BILLION KWh

Figure 19

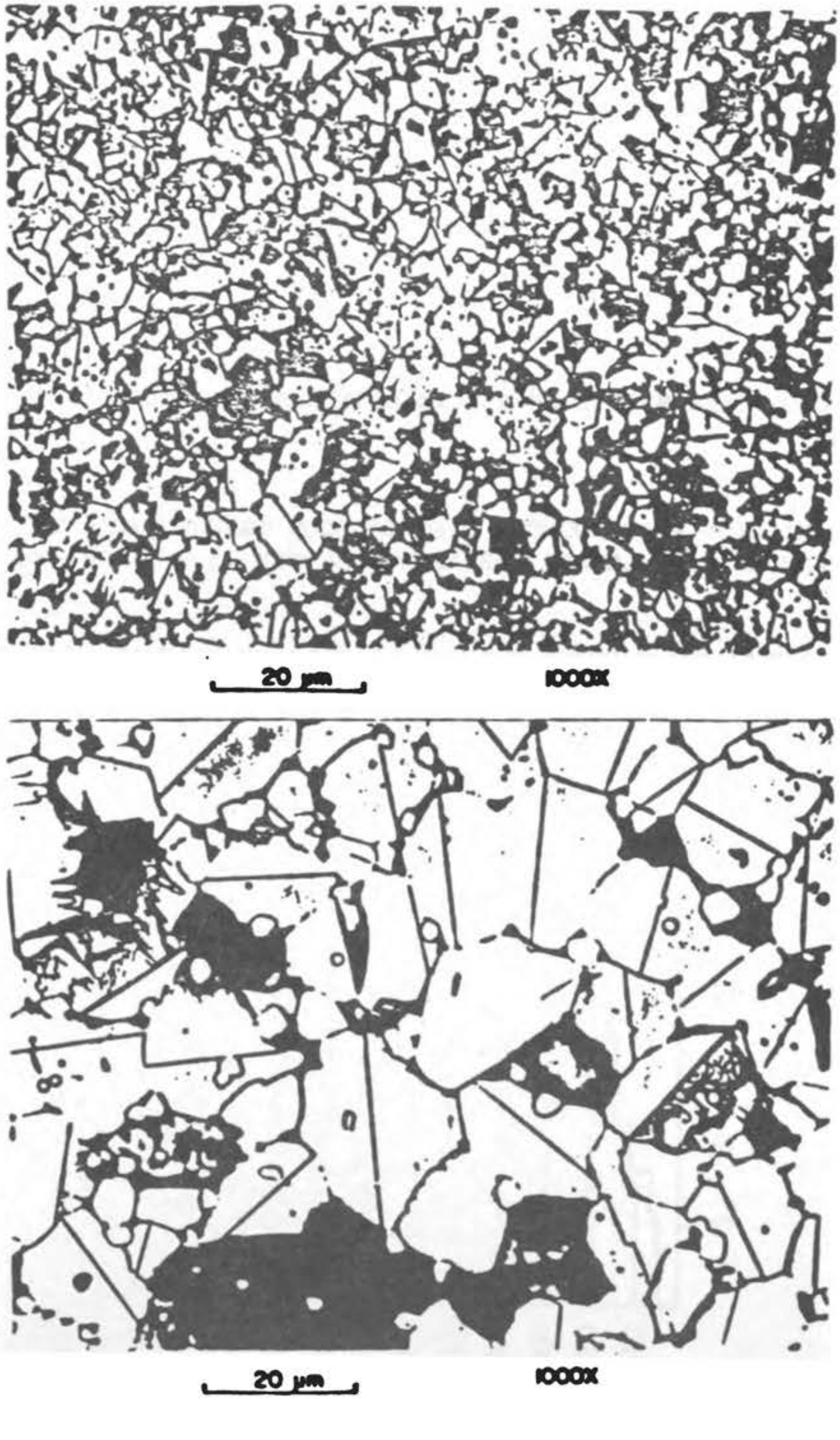

FIGURE 20 Very fine grain size is achieved by sol-gel.

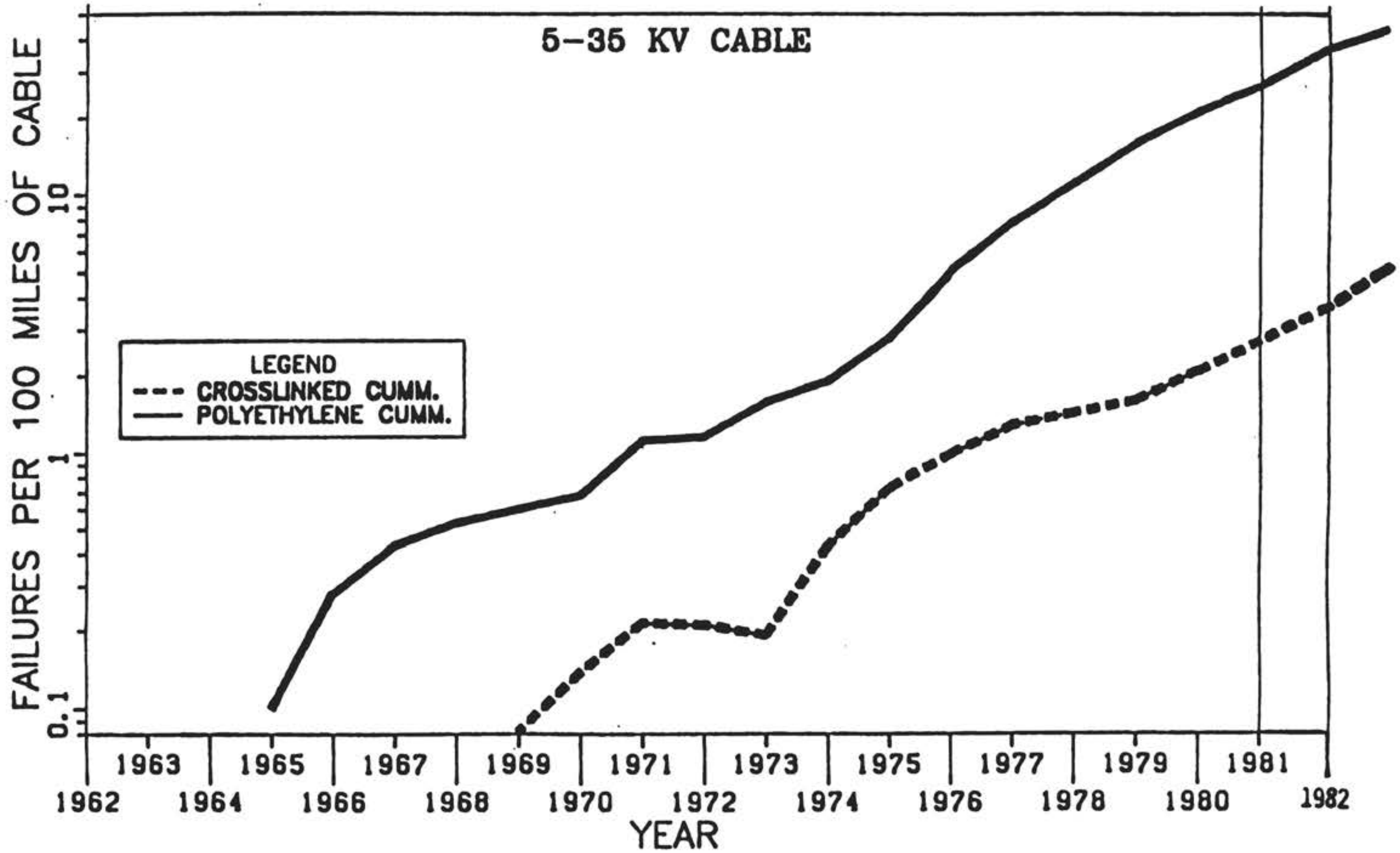

FIGURE 21 Twenty-one reporting companies electrical cable failure rate (cumulative).

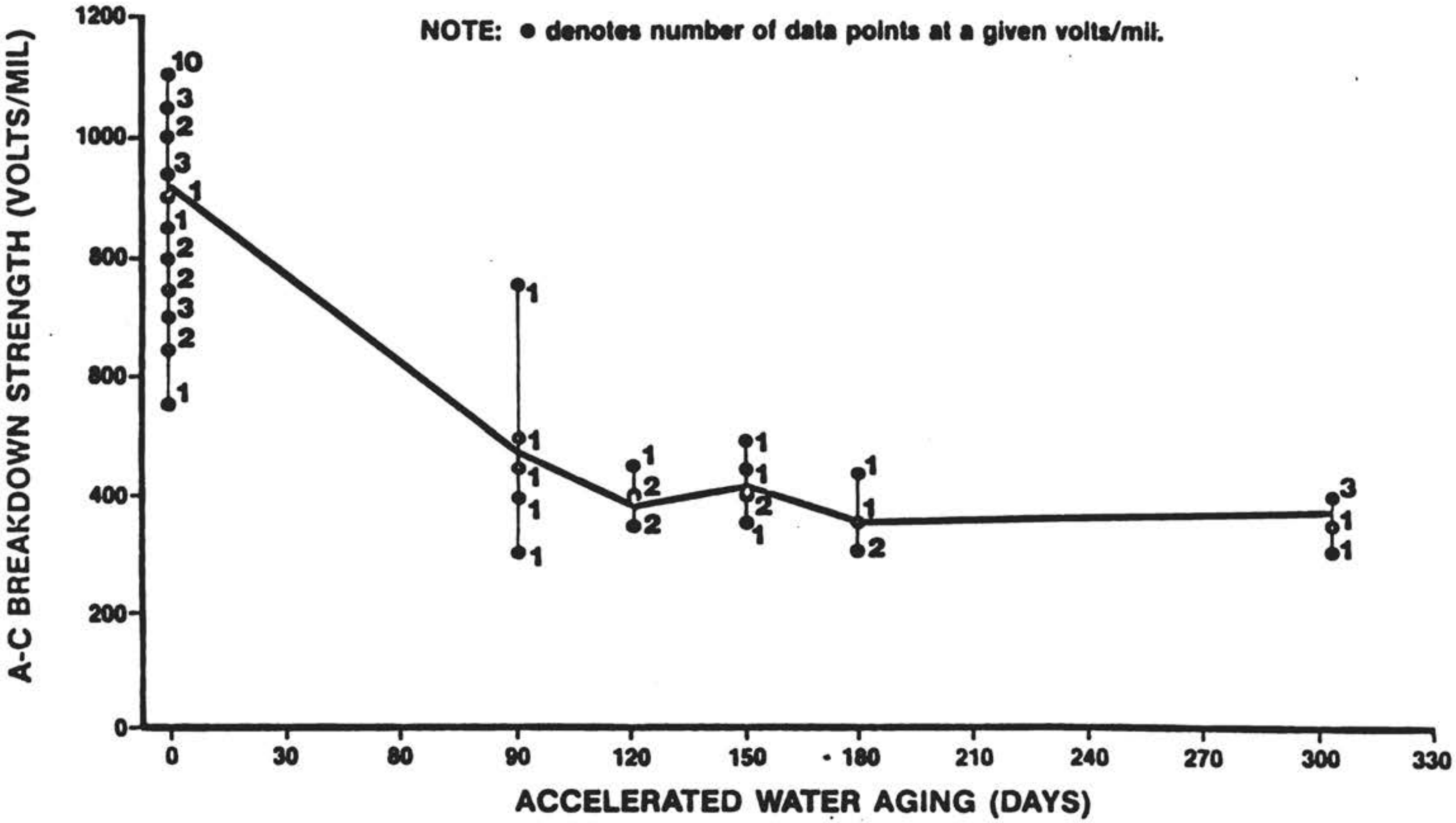

FIGURE 22 Results of AC dielectric strength tests on speciments of unaged and aged XLP compound.
Source: EPRI.

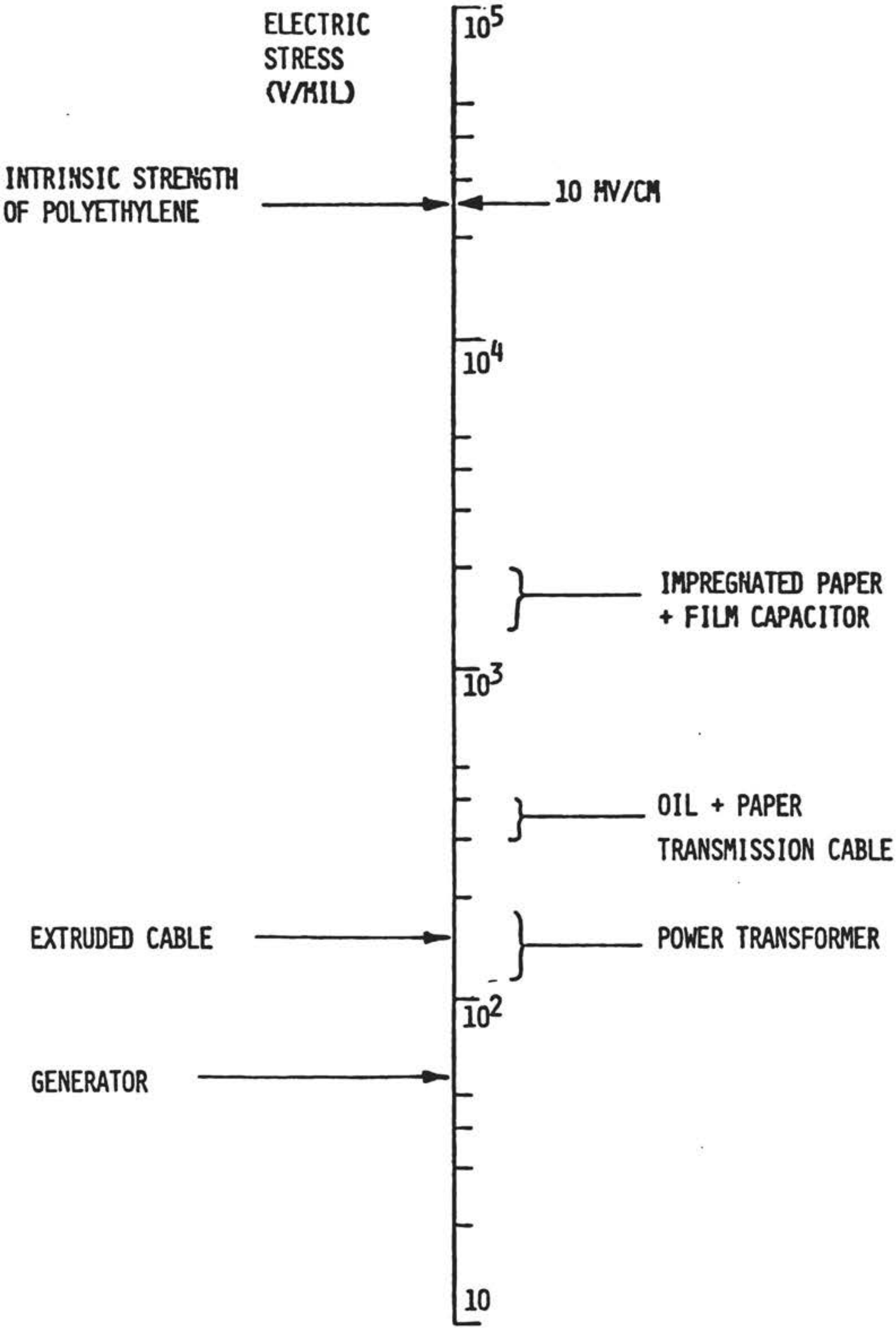

FIGURE 23

SOURCE: General Electric Company

- IMPROVED VOLTAGE GRADING
- HIGHER DIELECTRIC STRENGTH
  - -- REDUCE SIZE AND COST
- NEW WINDING/INSULATION SYSTEM
- ENVIRONMENTAL - FIRE RESISTANCE FLUIDS
- AUTOMATED ASSEMBLY
- SIMPLIFIED PROCESSING
- IMPROVED RELIABILITY

Figure 24 Transformers--benefits of new dielectric systems.
Source: Westinghouse Electric Corporation

- HIGHER OPERATING STRESS LIQUID/SOLID SYSTEMS
- ADDITIVES TO LIQUIDS FOR IMPROVED PERFORMANCE
- IMPROVED STRESS CONTROL
  - -- MATCHING SOLID/FLUID DIELECTRIC CONSTANT
- NONFLAMMABLE FLUIDS
- GASEOUS INSULATION?
- NEW WINDING DESIGNS FOR LOW LOSS, AND AUTOMATED ASSEMBLY
- DIAGNOSTICS
- STUDY STREAMER--FLASHOVER TRANSITION IN LONG GAPS
- MULTIFACTOR AGING STUDIES

Figure 25 Transformers--directions for new dielectric systems
Source: Westinghouse Electric Corporation

MAJOR

- REDUCED SIZE AND COST
    - -- INCREASED OPERATING FIELD E
    - -- KVA/UNIT (E)^2
    - -- HIGHER VOLTAGE/SECTION
- NEW COMPACT, LOW LOSS CAPACITOR CONFIGURATIONS
- IMPROVED LOW TEMPERATURE PERFORMANCE
- DRY, NONFLAMMABLE SYSTEMS
- OPERATE AT 30 PERCENT HIGHER STRESSES BY REDUCING OVERVOLTAGES

MINOR

- LOWER LOSSES--NOW VERY LOW
- BETTER THERMAL PROPERTIES

Figure 26 Capacitors--benefit of new dielectric systems.
Source: Westinghouse Electric Corporation

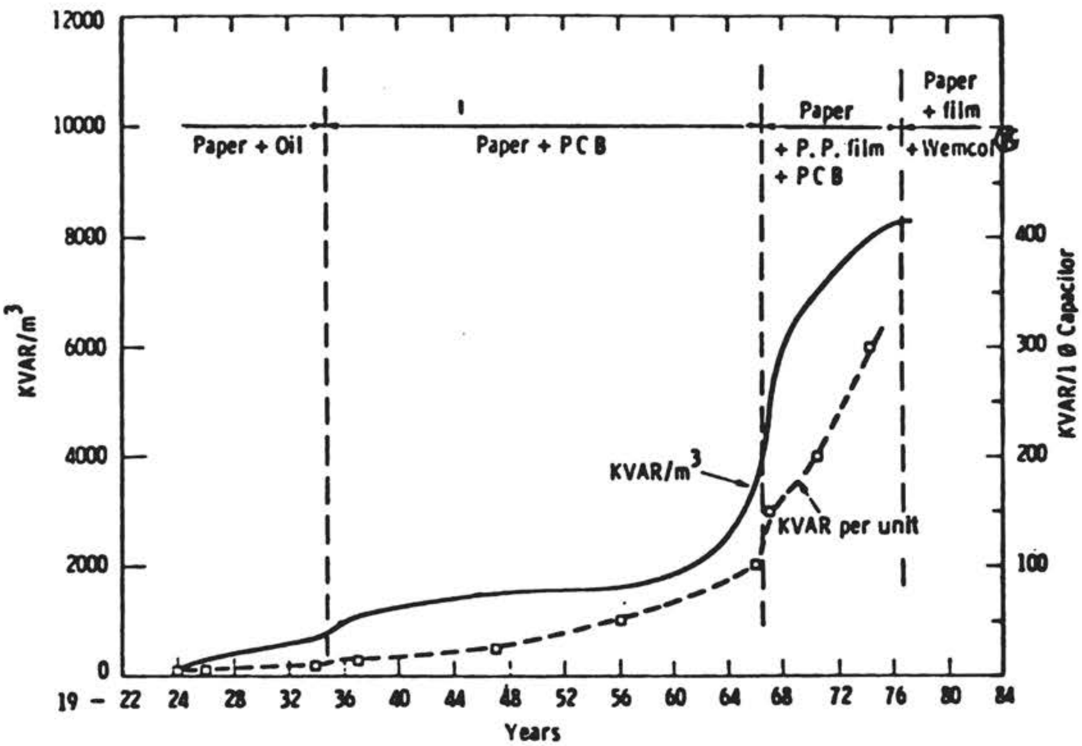

FIGURE 27 Power capacitor KVAR/m^3 and largest single phase capacitor versus manufacturing time.
Source: T. W. Dakin, IEEE Trans. Electrical Insulation, Vol. EI-13, No. 4, 1978.

MAJOR BENEFITS

-- REDUCTION IN INSULATION, 1/2 TO 2/3 THAT OF PAPER.

-- REDUCED CABLE DIAMETERS, SHIPPING WEIGHTS.

-- LONGER SHIPPING LENGTHS, FEWER JOINTS AND MANHOLES.

-- REDUCTION IN PIPE SIZES.

-- REDUCED PIPE FILLING OIL (APPROXIMATELY 50 PERCENT)

-- REDUCTION IN DIELECTRIC LOSSES TO 1/4 - 1/3 THOSE OF PAPER.

-- CHOICE OF OPTIMIZING CHARGING CURRENT AND INSULATION.

-- MODERNIZED, SUBSTANTIALLY REDUCED-SIZE JOINTS.

Figure 28 PPP - paper, polypropylene, paper laminate.
Source: Electric Power Research Institute; PPP Project RP7880

U.S. DEPARTMENT OF ENERGY

ELECTRIC ENERGY SYSTEMS DIVISION

MATERIALS PROGRAM

CONCENTRATE ON LONG-TERM, HIGH RISK POTENTIALLY HIGH PAYOFF RESEARCH THAT WILL HAVE THE GREATEST IMPACT IN:

- MEETING NATIONAL SECURITY
- PROTECTING PUBLIC HEALTH AND SAFETY
- PROVIDING A MORE COST EFFICIENT RELIABLE SYSTEM
- INTEGRATING A DIVERSIFIED RESOURCE BASE

Figure 29 Program strategy.

- STRUCTURE OF THE ELECTRIC INDUSTRY PRECLUDES LONG-TERM RESEARCH
  - -- CONSTRAINED THROUGH REGULATORY ACTIONS, POLICIES AND LEGISLATION
  - -- OFTEN REGULATORS ARE UNWILLING TO AUTHORIZE RISKY VENTURES
  - -- INDIVIDUAL UTILITIES FOCUS ON SHORT-TERM PROJECTS THAT IMPACT THEIR OPERATING ENVIRONMENT
- ENHANCE THE U.S. TECHNOLOGY BASE

Figure 30 Reasons for federal participation.

- MAINTAIN A DIALOGUE WITH THE PRIVATE SECTOR TO ENHANCE INFORMATION EXCHANGE AND TECHNOLOGY TRANSFER
- ENSURE AN AWARENESS OF RESEARCH BY THE RESPECTIVE ORGANIZATIONS (E.G., EPRI)
- SCREEN FOR FEDERAL PARTICIPATION
- IDENTIFY AND ASSESS ELECTRIC POWER RESEARCH OPPORTUNITIES IN ORDER TO MINIMIZE REDUNDANCY
- DISSEMINATE RESEARCH RESULTS TO THE SCIENTIFIC COMMUNITY
- ENCOURAGE ORGANIZATIONS TO COMMERCIALIZE TECHNOLOGIES

Figure 31 Program planning.

Prepared for:

DOE/OR/21400-3

U.S. Department of Energy

October 1984

Assistant Secretary, Conservation
and Renewable Energy
Office of Energy Systems Research
Under Contract No. DE-AC05-84OR21400

PROGRAM PLAN FOR RESEARCH AND DEVELOPMENT OF DIELECTRIC MATERIALS FOR ELECTRIC POWER SYSTEMS

United States Department of Energy

OBJECTIVES	E1—IDENTIFY CURRENTLY USED DIELECTRIC MATERIALS AND PROCESSES THAT CAN BENEFIT FROM IMPROVEMENTS	E2—INVESTIGATE FUNDAMENTAL MECHANISMS AND INTERFACIAL PHENOMENA OF DIELECTRIC MATERIALS	E3—DEVELOP FUNDAMENTAL UNDERSTANDING OF AGING AND ASSOCIATED FAILURE MECHANISMS OF DIELECTRIC MATERIALS	E4—DEVELOP DIELECTRIC MATERIALS FOR FUTURE POWER EQUIPMENT	E5—PROVIDE INFORMATION AND RECOMMENDATIONS FOR APPLICATION OF MATERIALS AND DESIGN CONCEPTS TO THE ELECTRIC POWER INDUSTRY
TO DEVELOP A FUNDAMENTAL UNDERSTANDING OF THE MECHANISMS OCCURRING WITHIN DIELECTRIC MATERIALS AND INTERFACIAL PHENOMENA	●	●	●		
TO DEVELOP DIELECTRIC MATERIALS AND CONCEPTS AND DETERMINE PERFORMANCE CHARACTERISTICS	●	●	●	●	
TO PROVIDE FOR TECHNOLOGY TRANSFER OF MATERIALS AND CONCEPTS FOR APPLICATION BY THE ELECTRIC POWER INDUSTRY				●	●

FIGURE 32 Relationships between the program objectives and the program elements.

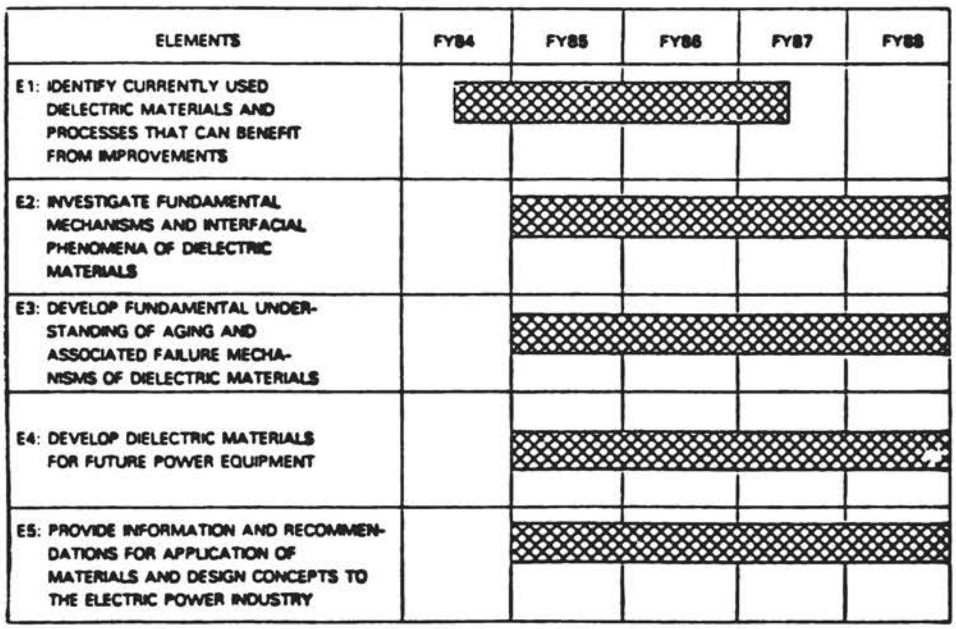

FIGURE 33 Time sequence of the program elements.

- FUNDAMENTAL STUDIES IN GASES, LIQUIDS, AND SOLIDS
- STUDIES OF INTERFACIAL PHENOMENA
- MULTIFACTOR AGING STUDIES OF POLYMER FILMS
- EMBRITTLEMENT STUDIES OF AMORPHOUS METALS
- ADVANCED METAL OXIDE VARISTORS
- CONDUCTING POLYMERS FOR STRESS GRADING
- TOXICITY STUDIES OF GASEOUS BY-PRODUCTS

Figure 34 Highlights of DOE/EES materials sponsored research.

- GASEOUS AND LIQUID DIELECTRICS: FUNDAMENTAL STUDIES
- GASEOUS DIELECTRICS: BREAKDOWN PRODUCTS AND TOXICITY
- INTERFACE PHENOMENA: GAS/SOLID
- HVDC GAS CABLE TEST METHODS
- ELECTRODE-SOLID DIELECTRIC INTERFACES
- EXTRUDED CABLE INTERFACE AGING
- MULTIFACTOR AGING AND EVALUATION OF POLYMERIC FILMS
- EMBRITTLEMENT STUDIES OF AMORPHOUS METALS
- DEVELOPMENT AND EVALUATION OF ADVANCED METAL OXIDE VARISTORS
- METAL OXIDED VARISTOR APPLICATIONS
- CONDUCTING POLYMERS FOR ELECTRICAL POWER EQUIPMENT
- EMP EFFECTS ON INSULATION SYSTEMS
- THERMAL STIMULATED CURRENTS IN POLYMERIC DIELECTRICS
- THRESHOLD VOLTAGE INVESTIGATION OF POWER CABLE INSULATION

Figure 35 DOE/EES material sponsored research FY 85.

- SUPERCONDUCTING GENERATOR
- SUPERCONDUCTING CABLE
- SYNTHETIC TAPE CABLE
- 1200 KV GAS CABLE INSTALLATION (DEVELOPED BY DOE/EES FROM 1978 THROUGH 1983) AND ACCESSORIES
- 600 KV PIPE TYPE DC CABLE
- 1200 KV GAS INSULATED TRANSFORMER

Figure 36 DOE/EES systems sponsored research.

THE DECLINE IN DOMESTIC R&D RESOURCES, ESPECIALLY IN MANUFACTURING COMPANIES AND THE INCREASING DEPENDENCE OF OUR UTILITY INDUSTRY ON OFF-SHORE TECHNOLOGY, ARE SERIOUS THREATS TO THE HEALTH AND SECURITY OF OUR NATION.

THE DAYS OF EDISONIAN APPROACH TO MATERIAL SELECTION IS FAST COMING TO AN END (OR SHOULD BE).

WITH INCREASING AVAILABLE AND AFFORDABLE SOPHISTICATED ANALYTICAL TECHNIQUES WE NOW HAVE THE OPPORTUNITY TO BEGIN TO BETTER UNDERSTAND THE FUNDAMENTAL CHARACTERISTICS OF MATERIALS AND THUS THE RESPONSE OF THE BUILDING BLOCKS OF THE ELECTRICAL POWER EQUIPMENT TO STRESSES AND ENVIRONMENT.

BASIC RESEARCH ON MATERIALS, DRIVEN BY THE NEED FOR IMPROVED EQUIPMENT AND PERFORMANCE, IS VITAL TO THE ELECTRICAL INDUSTRY OF THIS NATION IF IT IS TO KEEP ITS TECHNOLOGY BASE AND EMPLOY NEW MATERIALS IN INNOVATIVE AND MORE EFFICIENT SYSTEMS.

Figure 37 Conclusions.

APPLICATION OF SUPERCONDUCTORS IN ELECTRIC ENERGY SYSTEMS

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INTRODUCTION

A. Discovery of superconductivity

B. Development of practical liquid helium technology

C. Modern superconductors

D. Early experiments and suggested electric power applications

E. Revolutionary changes in technology not evolution by incremental change

1. New materials
2. New fabrication technology
3. Over proposing

POTENTIAL APPLICATIONS

A. Application list

1. Power transmission
2. Generation
3. Energy storage
4. Transformers
5. Fault current limiters

B. Discussion plan

1. Application description
2. Current status
3. Prospects with current materials and technology
4. Prospects with future materials and technology

POWER TRANSMISSION

A. Application description

B. Current Status

1. United States
2. Japan

C. Prospects with current materials and technology

D. Prospects with future materials and technology

GENERATION

A. Application description

1. Configuration

   a. Rotor
   b. Air gap
   c. Armature

2. Advantages

   a. Efficiency
   b. System stability
   c. Small size and weight
   d. High voltage
   e. Cost
   f. Reliability

B. Current Status

1. United States
2. Japan
3. Germany
4. France
5. United Kingdom
6. Soviet Union

C. Prospects with current materials and technology

D. Prospects with future materials and technology

ENERGY STORAGE

A. Application description

B. Current status

C. Prospects with current materials and technology

D. Prospects with future materials and technology

TRANSFORMERS

A. Application description

B. Current status

C. Prospects with current materials and technology

D. Prospects with future materials and technology

FAULT CURRENT LIMITERS

A. Application description

B. Current status

C. Prospects with current materials and technology

D. Prospects with future materials and technology

FUTURE DEVELOPMENT PROGRAM RECOMMENDATIONS

A. National needs

1. General public
2. Utility industry
3. Electrical equipment manufacturers

B. Foreign competition

1. Industrial
2. Research

C. National policy

1. Promote productive profitable industry
2. Promote investment in science and technology

D. Government role

1. Promote basic science and technology

2. Operate with industry
3. Invest in intermediate time scale technology

E. U.S. Department of Energy Role

1. Superconducting technology
2. Application to generation
3. Application to transmission

HAWAII DEEP WATER CABLE PROGRAM

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INTRODUCTION

The Hawaii Deep Water Cable (HDWC) Program is a research and development project directed toward extending the state of the art in high voltage direct current (HVDC) submarine cable design, deployment, retrieval, and repair. This paper provides a review of the HDWC Program goals, discusses the major technical issues involved, describes the technical approach being pursued, and summarizes the program's status and expected benefits.

The state of Hawaii is nearly completely dependent on imported fuel for electric power generation. The original stimulus for the HDWC Program was the state's interest in developing its abundant renewable alternative energy resources, particularly its geothermal resources on the island of Hawaii. The development of an electric intertie between the islands of Hawaii and Oahu is crucial to the development and use of this major geothermal resource.

The program is being funded by the U.S. Department of Energy (DOE), Division of Electric Energy Systems (EES), and the state of Hawaii Department of Planning and Economic Development (DPED). The HDWC Program was formulated in late 1979 and early 1980. State support began in 1981, and in September 1982 the federal program was officially initiated with a contract between DOE and Hawaiian Electric Company, Inc. (HECO).

The HDWC Program was established to be consistent with DOE's objectives of pursuing meaningful energy research and development, encouraging energy conservation, supporting technologies that utilize renewable resources, and, ultimately, providing an adequate and reliable source of energy at the lowest reasonable cost to consumers. The HDWC Program is within the "System Technology" element of the EES/DOE program, which is directed toward increased system efficiency, fuel displacement, and improved resource management.

The federally funded portion of the HDWC Program is structured to provide technical information of benefit not only for the Hawaii application, but for other national and international applications and for the utility and cable industry in general. At the same time, the state is funding those elements of the HDWC Program that are directly related to the application of HVDC submarine cable technology in Hawaii.

PROGRAM OBJECTIVE AND GOALS

The objective of the HDWC Program is to determine the technical feasibility of deploying and operating a submarine power transmission cable between Kohala on the island of Hawaii and the Makapuu area of Oahu over a service life of at least 30 years.

Associated primary goals of the program are:

- to determine the technical and economic feasibility of establishing a submarine power transmission cable system in water depths of up to 2,100 m (7,000 ft) and over a distance of more than 240 km (150 mi);
- to identify solutions to the ocean engineering problems of deploying, retrieving, and repairing a submarine power cable in the Hawaiian environment; and
- to develop a commercial cable criteria document that can be used by private industry or governmental agencies for the design, installation, and maintenance of submarine power transmission cable systems.

Secondary goals of the program are:

- to establish HVDC submarine cable design, manufacturing, installation, and maintenance capability in the United States by U.S. firms;
- to provide incentive, through HVDC submarine transmission system availability and reliability, to the development and use of renewable energy resources; and
- to gather empirical information that may be used to assess present HVDC submarine cable design and testing standards.

MAJOR TECHNICAL ISSUES

The major technical issues in this program relate to the coordinated design, testing, and evaluation of an VDC deep water submarine cable, cable handling equipment, and cable vessel.

To date, the deepest and longest HVDC submarine cables are the "Skagarrek" cables installed between Norway and Denmark. These cables are deployed to a depth of 550 m (1,800 ft) and span a distance of 126 km (78 mi). Other existing submarine cable systems that have been installed are in far more shallow waters and span shorter distances. Existing submarine power cable systems are generally installed in areas that are relatively free of adverse wind, wave, and water current conditions, i.e., are in protected, shallow water areas with stable, benign bottom conditions.

In contrast, the Hawaii submarine cable application being considered in the HDWC Program requires cable installation in water depths almost four times greater than those to which present state-of-the-art cable design has been applied. The mechanical performance characteristics of the cable and splices subjected to these severe installation depths are of concern in the HDWC Program, particularly in light of the fact that the maximum mechanical capability of existing cable designs has not been clearly identified. Typical practice is to subject cables to an acceptance test related to the specific installation requirement, rather than to characterize the cable fully, including tests to failure.

Beyond the severe depth requirement, the HDWC Program involves deployment and retrieval in unprotected ocean areas where winds are approximately 35 knots, corresponding surface waves are approximately 2.44 m (8 ft), and surface currents are around 3 knots. Other potential open-ocean submarine cable applications are likely to be subject to similarly severe environmental conditions. Therefore, the models used to develop deep water submarine cable designs and the mechanical performance of the cable and splices subjected to potentially severe transient mechanical loads are key factors in the determination of technical feasibility.

Current cable installation practice has not included the evaluation of dynamic characteristics of the deployment vessel and cable, or development of control algorithms for deployment. In these shallow water installations the tension on the cable during deployment is estimated by a rule of thumb (1.3 x the weight of the cable in the water); bottom tension on the cable has been controlled by monitoring total tension at the vessel. Unprotected deep water installations are subject to a much larger dynamic tension component during cable deployment and retrieval, which must be quantified to guarantee that the cable is not damaged. Therefore, a cable deployment control system must be developed and tested for the HDWC Program. Validation of the dynamic models and testing of the control algorithms developed for cable deployment and retrieval operations are additional technical issues under consideration.

Finally, existing cable-laying vessels and cable handling equipment (CHE) are incapable of deploying or retrieving a power cable in water depths on the order of 2,100 m. This equipment must be designed and evaluated to determine technical feasibility, considering the high static and dynamic mechanical loads they must withstand. The design of the vessel and individual equipment components is not beyond the current state of the art and is not the technical issue of concern. Rather, the technical development problem is to coordinate and integrate component equipment designs to ensure an overall vessel-CHE system that has adequate dynamic performance characteristics in the severe sea conditions envisioned.

TECHNICAL APPROACH

The HDWC Program approach to determining the technical feasibility of the deep water submarine cable concept is a straightforward one: Design, fabricate, and test cable, cable handling equipment, and vessel subsystems and evaluate their performance. The performance of these three major subsystems is evaluated against defined system and subsystem level feasibility criteria that reflect performance requirements of and constraints to a hypothetical baseline commercial cable system. A flow chart of HDWC activities is shown in Figure 1.

HDWC Program technical feasibility determination is based on a thorough testing program. The major thrust of the cable laboratory test program will be to: (1) verify that the selected cable design meets or exceeds all cable subsystem feasibility criteria related to installation, operation, maintenance, and repair; (2) evaluate the response of the full-scale cable to typical stresses (electrical, mechanical, and thermal) that may be encountered; (3) determine the cable design maximum capability; and (4) confirm theoretical models used in the development and evaluation of the cable design. The cable laboratory test program will provide a complete quantitative characterization of the electrical, mechanical, thermal, and hydraulic capabilities of the full-scale cable and the performance of its component parts.

Determination of the design cable maximum capability is particularly important in light of uncertainties in submarine bottom conditions, deployment/retrieval weather and sea conditions, and subsurface currents. Further, recognizing that an actual commercial cable system design may differ from the hypothetical baseline design developed and tested in the HDWC Program, test data will be obtained that are sufficient to allow future commercial design interpolations or extrapolations to be made with reasonable confidence.

Similarly, the cable vessel and cable handling equipment subsystems will undergo extensive testing prior to acceptance to ensure, as far as is practical, that these subsystems will operate, as designed, in the field. To aid in the design of these subsystems, at-sea surveys to determine sea bottom characteristics have been performed. Additionally, current measurements, both at the surface and through the water column have been or will be taken. These measurements, along with surface wave and wind speed measurements, are being integrated into equipment and vessel design/feasibility criteria.

Further test data will be collected to allow: (1) evaluation of cable vessel handling and response for cable deployment and retrieval; (2) determination of the adequacy of present-day equipment (control and handling systems, instrumentation, etc.) to manipulate the cable without causing damage or undue stress; (3) evaluation of the ability of the cable vessel and cable handling equipment to place and tension a cable within specified limits on the bottom; (4) evaluation of the feasibility of redeploying a cable with a repair splice; (5) evaluation of cable deployment and retrieval methods for various sea state conditions, a range of cable vessel speeds and cable payout rates, and

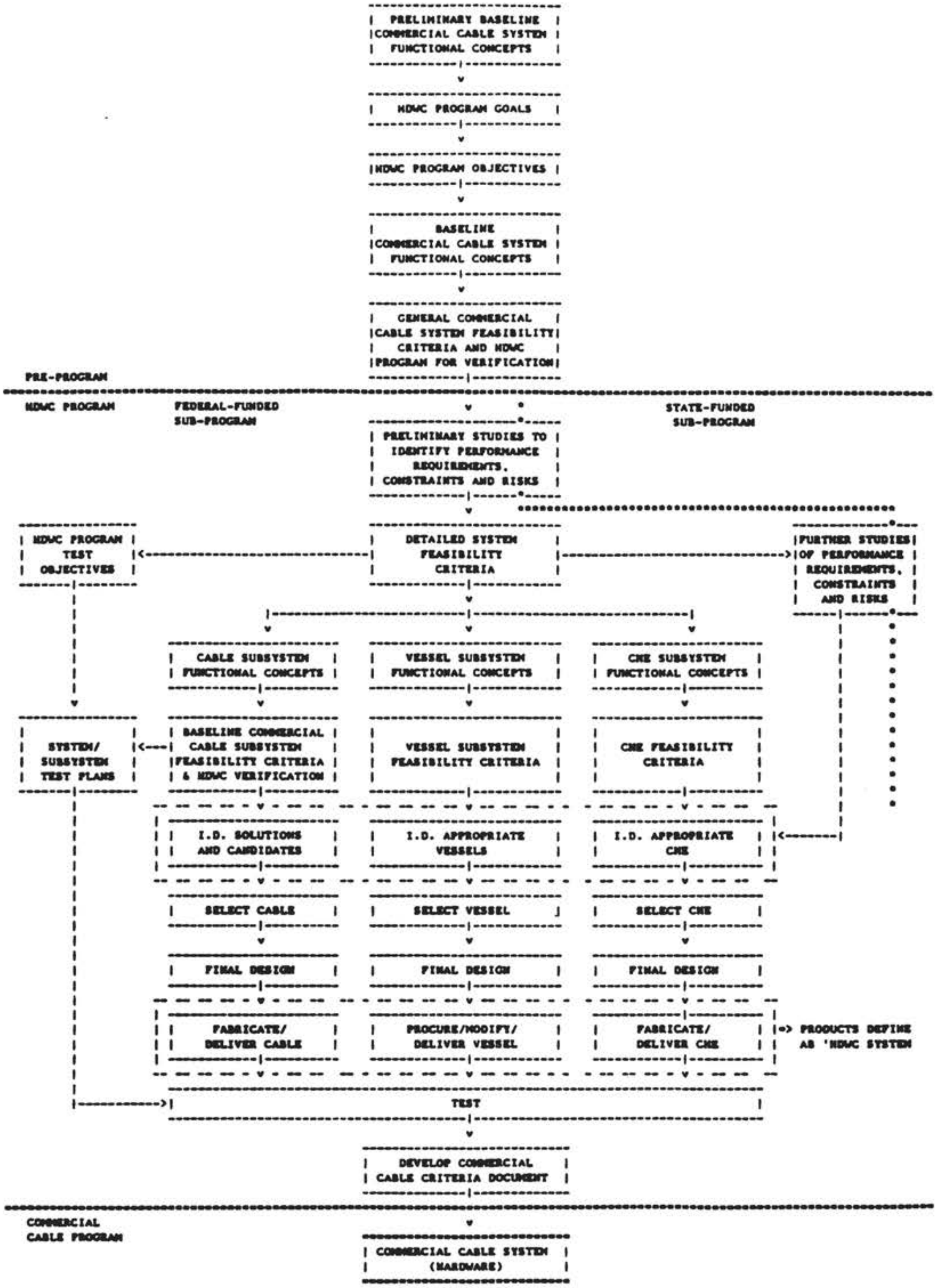

FIGURE 1 HWDC program technical activities flow chart.

cable laying up-slope versus down-slope; and (6) confirmation of predicted cable vessel responses to allow extrapolation for modified cable-handling equipment and vessel designs in the future. Additional testing will allow verification of the test limits and methods used in laboratory testing of the cable.

PROGRAM STATUS/ACCOMPLISHMENTS TO DATE

The most significant advances in the HDWC Program thus far have been within the cable subsystem. From the cable subsystem feasibility criteria, a cable design selection methodology was developed. This selection methodology was then applied to design data developed in a comprehensive parametric study to select a specific cable for final design, fabrication, and testing. The selected cable is a self-contained, oil-filled (SCOF) design, ±300kVdc, 250-MW aluminum conductor cable. The internal structure of the cable is shown in Figure 2. Following this selection decision, other cable subsystem planning, design, and development efforts are proceeding.

Ongoing activities include the development of a cable repair rationale, a cable transportation plan, final cable accessories design activities, and preparation for extensive laboratory cable testing. Fabrication of a laboratory test length of cable [approximately 1,068 m (3,500 ft)] is expected to begin later this year (1985) with laboratory testing to be initiated in early 1986.

In parallel with the cable subsystem advances, work proceeded on the cable vessel and cable handling equipment subsystems. For each of these subsystems, preliminary feasibility criteria were prepared, available systems inventoried and design development and concept studies initiated. Figure 3 indicates the preliminary concept of the deck layout for cable handling equipment.

PROGRAM OUTPUTS/BENEFITS

Currently there are no proven power transmission systems available for crossing deep, unprotected ocean waters. This program is expected to determine the technical feasibility of establishing HVDC submarine cables in water depths of up to 2,100 m (7,000 ft), an extension of present technology that will allow cables to be installed in water depths almost four times greater than at present. This technology has potential application to proposed projects off both the east and west coasts of the United States, as well as direct application to the state of Hawaii. The technology developed will be beneficial to those coastal states or nations that are investigating alternative energy resources located far from market areas and, therefore, require a relatively environmentally benign means of transporting energy. Known direct applications of the technology to be developed include proposed submarine cable projects linking Canadian hydropower to the United States, the Bahamas to Florida, and Alaskan hydropower to the mainland

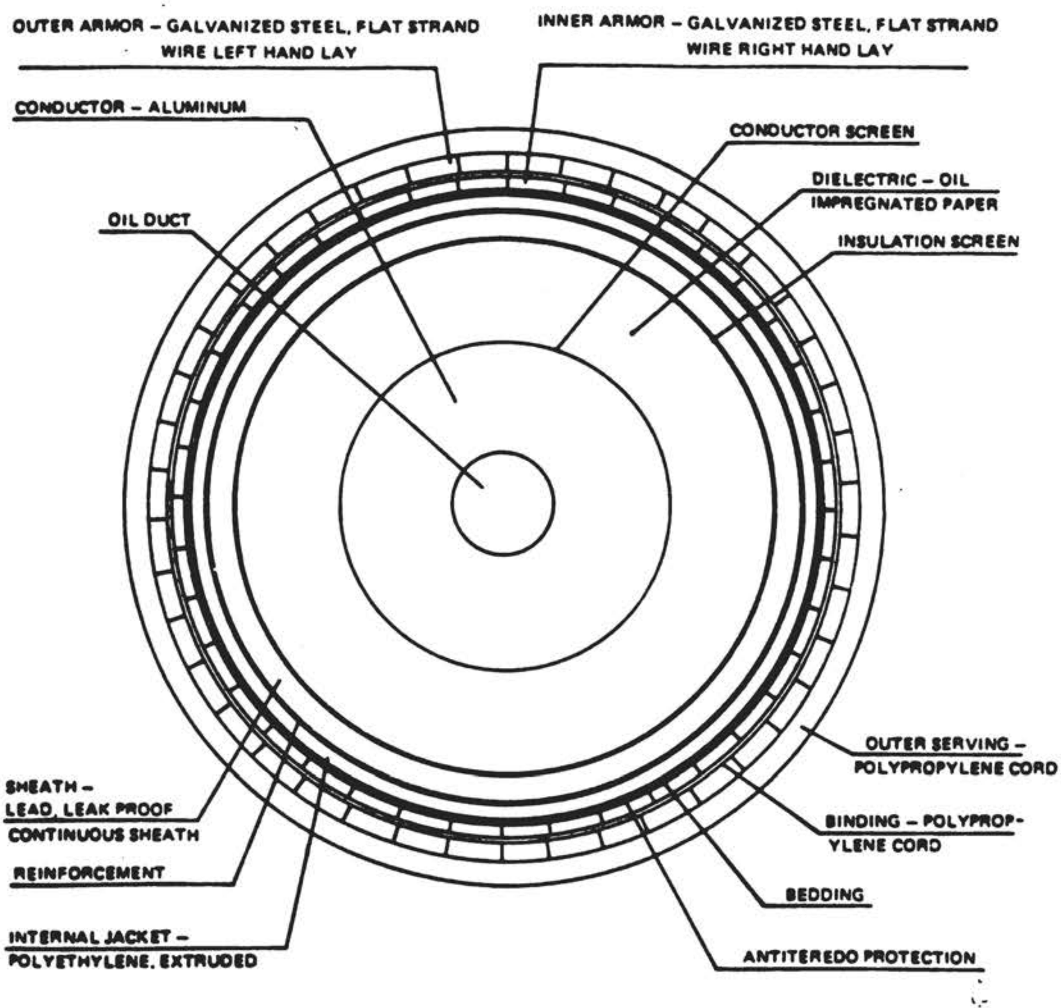

FIGURE 2 Typical SCOF cable cross section.
Source: Pirelli Cable Corporation, HWDC Program, October 12, 1983.

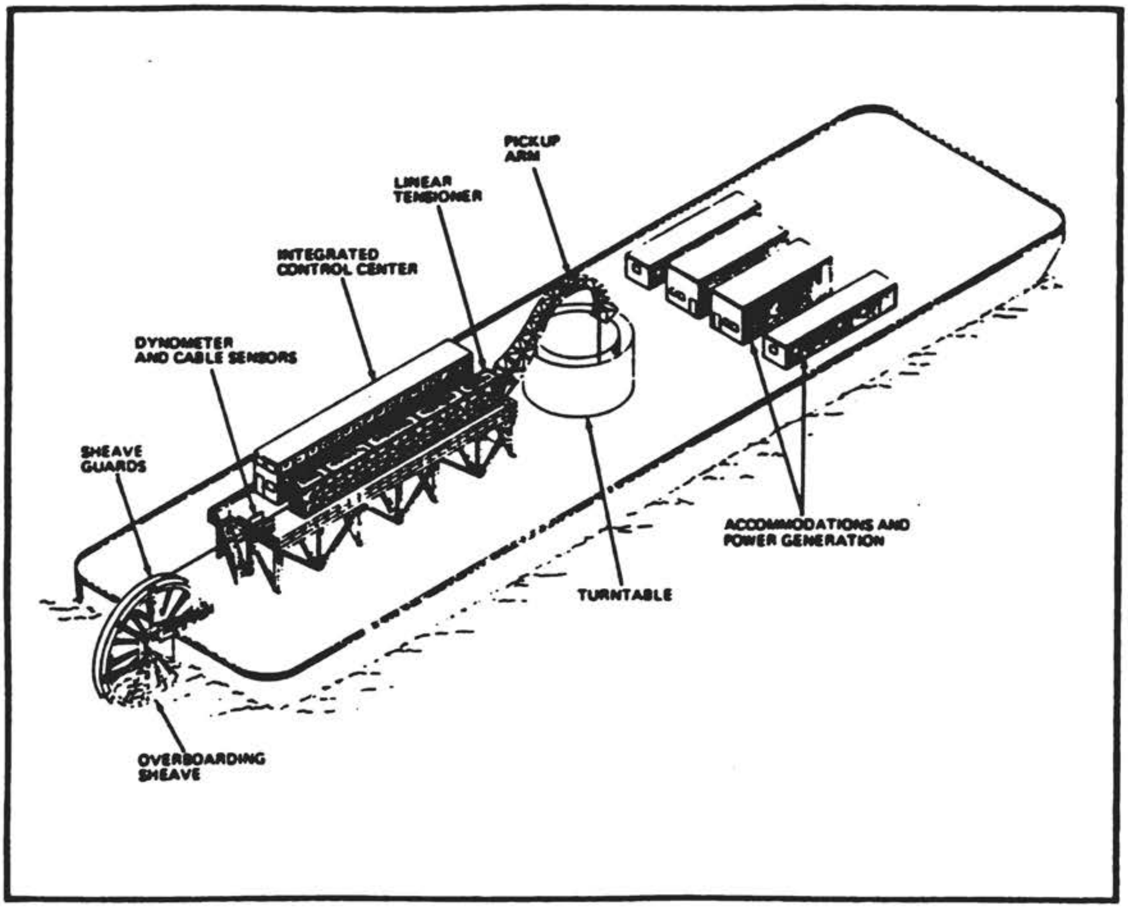

FIGURE 3 Hawaii deep water cable program cable vessel deck layout concept.
Source: Western Gear Machinery Company, January 1985.

United States; and intertying the Hawaiian Islands. If the concept proves to be technically feasible, an interisland transmission system could be pursued commercially. Such a system would allow energy from proven geothermal resources on the island of Hawaii to supply 80 percent of the state's forecasted electrical energy demand.

The HDWC Program will result in the characterization of pertinent cable, cable vessel, and cable handling equipment design and operational factors. This will provide the industry with a quantitative indication of the level of "overdesign" or "safety factor" in the cable, and should assist in future optimization of all submarine cable designs, whether for deep water or shallow water application.

Additionally, the technical task work being performed by U.S. companies will concurrently develop an exportable expertise that can be applied internationally.

The results of the work undertaken in the HDWC Program will be published in technical reports and national and international professional society publications, and will be summarized and published in a program final report that will be submitted to and published by DOE. It is expected that the state of the art in cable design, vessel design and operation, and cable handling equipment design and operation will be extended to the benefit of public and private utilities, governmental agencies, and the scientific community at large.

A CONSERVATIVE VIEW OF HIGH VOLTAGE DIRECT CURRENT POWER TRANSMISSION

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ABSTRACT

High voltage direct current (HVDC) power transmission systems are a comparatively recent addition to the North American interconnected bulk power transmission network. They serve an important role as an adjunct to alternating current (ac) systems in providing reliable, cost-efficient delivery of electric energy. This paper describes how HVDC systems have a distinct energy conservation role in electric power transmission systems. It also illustrates how the development of HVDC has been conservative, not speculative, and gives examples of areas in which continuing research support can be beneficial.

INTRODUCTION

Electric power systems in the United States deliver alternating current (ac), transmitting power at voltages of up to 765,000 volts. The efficiencies of high voltage ac transmission are well known. The decision to utilize alternating current rather than direct current (dc) was made around 1890. History records that Thomas Edison, a dc proponent, and George Westinghouse, an ac proponent, exchanged harsh words over the merits and demerits of the two systems, including their relative safety. Westinghouse, of course, won out.

Modern HVDC power transmission dates from 1954 with the installation of the 20-MW Gotland Island system using mercury arc valves. Today there are nearly 40 systems in operation or under construction. The newer systems use thyristor valves. Figure 1 illustrates the North American activity (Reeve, 1984). Systems in operation or under construction are solid; those under serious consideration and likely to be built are dashed.

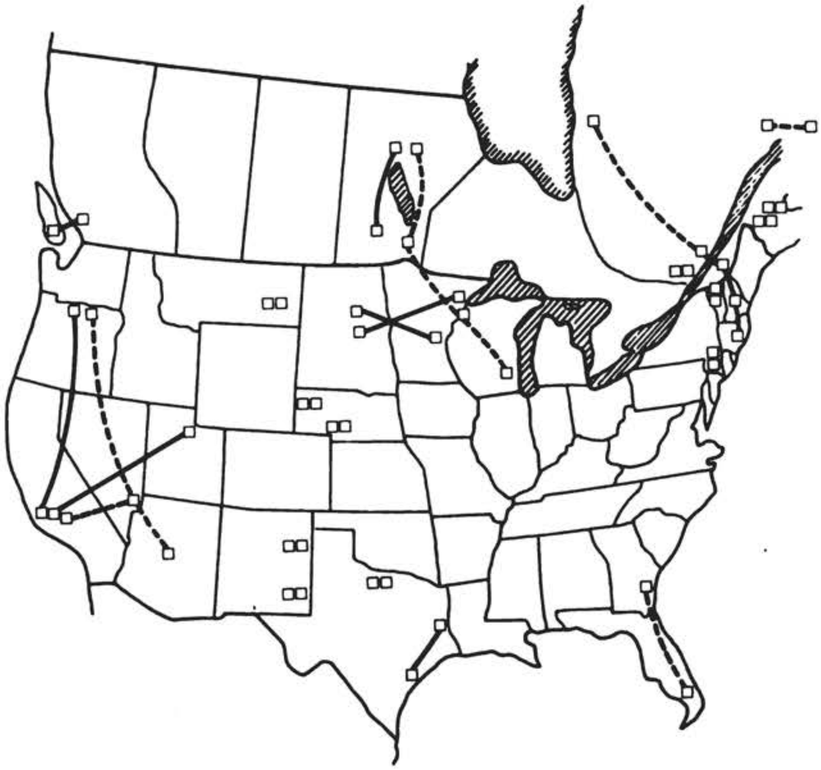

FIGURE 1 North American HVDC systems.

CHARACTERISTICS OF HVDC SYSTEMS

HVDC can offer cost advantages for long distance overhead or intermediate distance undersea transmission, and the concept of the "break-even distance" (beyond which dc is more economical than ac) is often raised in these evaluations. However, there are operational advantages accruing to dc that merit consideration:

1. Asynchronous connection--the two interconnected ac systems need not be in synchronism.

2. Controllability--a current or power order can be set and maintained and modulated to improve the dynamic performance of the associated ac system. The ordered current flows over the dc system-- not throughout the underlying ac system.

3. Reliability--in the event of a fault on one pole (+ or - conductor) of a dc system, earth return can be utilized to carry the current of the health pole. Thus, in excess of 50 percent of rated power can be transmitted (assuming temporary overload). For those dc systems that comprise series connections of converter bridges, operation at reduced voltage can be achieved if pollution-caused flashovers are occurring at full system voltage.

4. Low short circuit currents--dc line fault current is typically limited to two per unit by the system controls. Also, by virtue of the previously mentioned asynchronous connection and controllability features, the dc link does not contribute to the short circuit current of the interconnected ac system.

Energy conservation can be illustrated in all of the above systems; for example, consider asynchronous connection. The systems in Figure 1 without transmission lines or cables are back-to-back systems used to decouple the two ac systems. These are installed in locations where energy transfers are desired but ac synchronization is undesirable or impossible. The asynchronous importation of hydropower from Quebec into New England displaces oil-fired generation. (The longer range implications of using U.S. dollars to build hydro generation in northern Quebec rather than coal-fired or nuclear generation in this country are not considered here. Such decisions are in the realm of what is politically realizable given a moribund nuclear power industry and increasing concerns over acid rain. The principal disadvantages of dc are:

1. Reactive power requirements are approximately 50 percent of the megawatt power rating at each converter station.

2. Current harmonics are generated and must be prevented (by filters) from entering the ac system.

3. DC circuit breakers are still in the prototype stage of development; dc networks are just beginning to receive serious considerations.

These disadvantages point to areas in which further research can be beneficial.

Elements of an HVDC Transmission System

The most straightforward way to examine dc systems is to consider two isolated ac systems connected through a single dc link. Figure 2 illustrates this configuration. At the two ends of the dc system the Graetz bridge converters are represented as controllable batteries V_R and V_I. The transmission line is represented by lumped

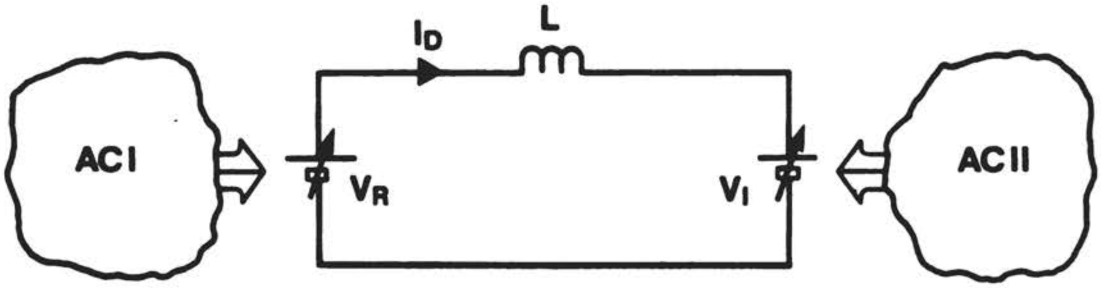

FIGURE 2 HVDC representation.

inductance L^R, and system resistance is neglected. A direct current I_D exists, and the system is in steady state.

Power flow is from left to right; in the dc system, V_R represents a source of energy and V_I represents a sink (load). V_R is a rectifier, and as with any rectifier it takes power from the ac system and converts it to dc. This could be accomplished by diodes, but for reasons of controllability it is achieved by thyristor valves. The system inductance ensures a relatively ripple-free direct current I_D. This current is forced into the inverter against a counter-voltage V_I. This inverter converts the dc power to ac power in synchronism with its associated ac system.

Figure 3 shows the components necessary for the functioning of an HVDC power system. On the ac side, harmonic filters and reactive compensation are required. The converter transformer isolates the ac system from the dc system. The Graetz bridge may represent series or parallel connected bridges, depending on system voltage and current. Both bridge and system controls are needed. DC harmonic filtering is required, as is a smoothing reactor for both ripple filtering and fault current rate-of-rise control.

The Graetz bridge is the principal component in the switching process, the ac/dc or dc/ac conversion. There are 12 converter valves comprising a 12-pulse bridge, as illustrated in Figure 4. The valves are arrays of series-connection thyristors; a single thyristor may be rated 5 kV, 2500 A. The solid state thyristors are electronically controlled current switches in that they "route" current according to which valve is conducting. They can block either a forward or reverse voltage; they will conduct if given a gate or firing pulse while

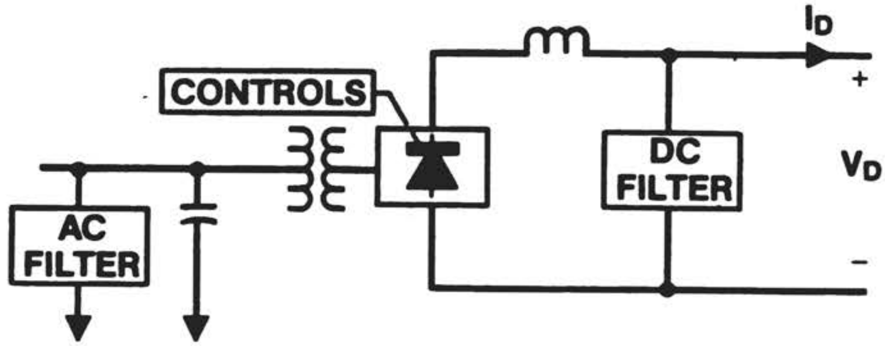

FIGURE 3 HVDC terminal components.

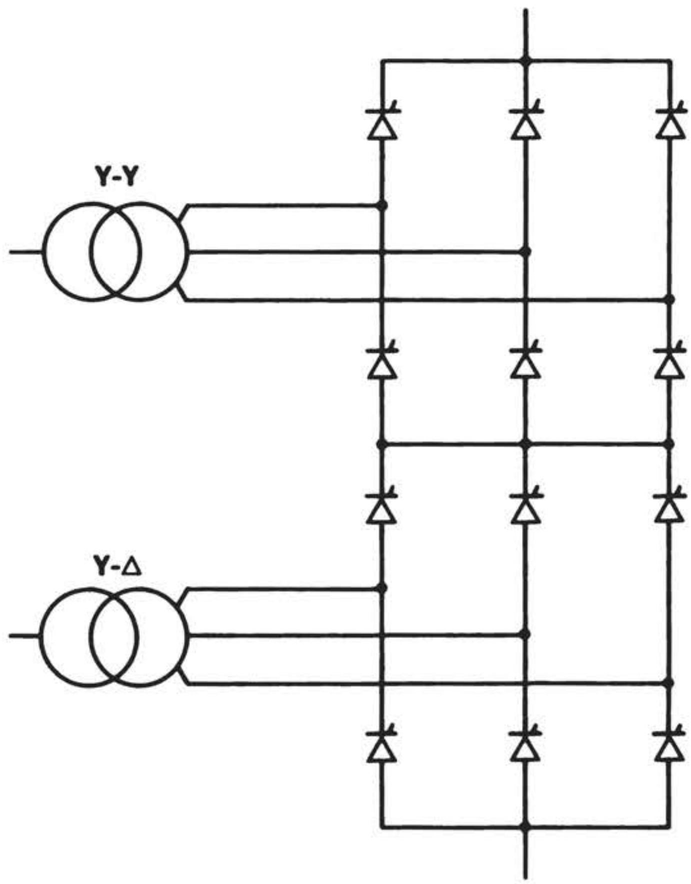

FIGURE 4 Twelve pulse Graetz bridge (three quadrivalves).

forward biased. They cease conduction at a subsequent current zero. Thyristors cannot "off-switch."

Earlier HVDC systems employed 6-pulse bridges. The present technology uses a 12-pulse configuration with wye-delta and wye-wye transformers. This allows converter valves to be arrayed in three groups of four "quadrivalves." An additional benefit is the elimination of some harmonic currents.

The controllability feature of dc systems derives from the controllable "turn-on" of the valves in the bridge. To rectify, a positive voltage must be passed upward and a negative voltage must be passed downward. The gate pulses are timed to arrive as a positive voltage appears across each valve in turn. Controllability is achieved by the timing of these gate pulses. Delaying the gate pulse after the zero crossing of the positive-going valve voltage decreases the bridge output voltage. From Figure 2, then, controllability of the rectifier and inverter voltages results from electronic control of the timing of the gate pulses. The output voltage is proportional to the cosine of the delay angle.

If the delay angle exceeds 90 degrees and moves toward 180 degrees, the bridge voltage becomes fully negative. This now corresponds to inversion--dc to ac conversion. Current from the rectifier is literally forced into the inverter against a counter-voltage provided by the ac system. The inverter converts dc power to ac power in synchronism with the ac system. Timing is such that current is injected into the ac system in proper phase relation to the already existing ac voltage. Both the rectifier and the inverter are line commutated converters. AC system voltages must be present; however, they need not be in synchronism.

The nature of the commutation process (transfer of current from valve to valve) is such that the delay angle must be constrained away from the zero and 180-degree limits of rectification and inversion. In the inverter, a margin angle must be maintained where the current zero in a valve occurs prior to the arrival of the positive-going voltage. The phase relationship between ac current and voltage is as indicated in Figure 5, and VARs are required at both converters. The amount of reactive compensation is on the order of half the real power conversion capability, supplied to each terminal.

Another consequence of the sequential switching of the converter is that currents on the ac side of the converter transformer appear as pieces of square waves (if I_D is constant). This results in harmonic currents, which must be prevented by filtering from entering the ac system.

Controllability of HVDC Systems

Current (hence, power) control is coordinated between the rectifier and the inverter in Figure 2. Normally, the rectifier controls current while the inverter establishes the dc link voltage. (They may interchange control functions under abnormal conditions.) In steady

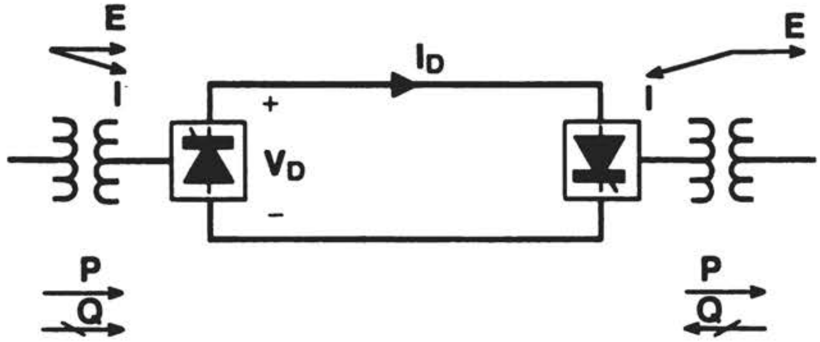

FIGURE 5 AC-side relationships for HVDC systems.

state, V_R exceeds V_I by the resistive line drop (here neglected). To increase the current I_D, the rectifier voltage V_R would have to be increased, creating a voltage drop across the inductance--hence, an increase in current. Upon reaching the new current level, V_R returns to its previous value ($=V_I$). Thus, it can be seen that substantial current (hence, power) changes can be attained by relatively small changes in rectifier voltage. This point is important. A dc system can respond to power order changes very quickly.

The system operating characteristic (V-I curve) is shown in Figure 6. The dotted lines represent the idealized control system, wherein the dc voltage is determined by the inverter and the dc current by the rectifier. (The delay angle is varied by closed loop control until the rectifier voltage is at the proper value in excess of the inverter voltage to establish the desired current.) The solid lines represent the normal (albeit simplified) control system characteristic. The rectifier has, in addition to the current control segment, a minimum delay angle or maximum available voltage limit. The droop results from a current dependent voltage loss from the switching (commutation) process in the converter. It can be thought of as an equivalent internal impedance. The inverter has a backup current control (used in the event of sudden decreases in the rectifier voltage). The formerly flat voltage-controlling portion now droops--a result of an internal voltage loss as with the rectifier.

As a further comment on controllability and reliability, consider the response of a bipolar dc system to a line-to-ground fault (Figure 7). Prior to the fault, current I_D flows in all four converters. In response to the fault, the two positive pole converters shut down by control action. Current continues to flow in the negative pole

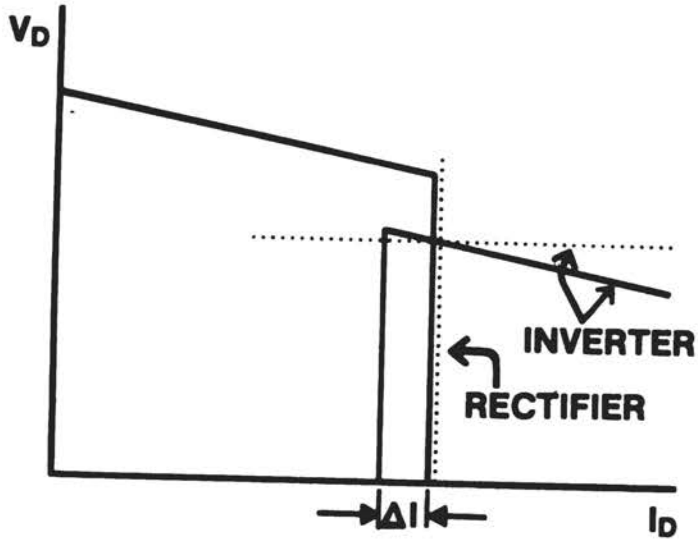

FIGURE 6 Converter V-I curves.

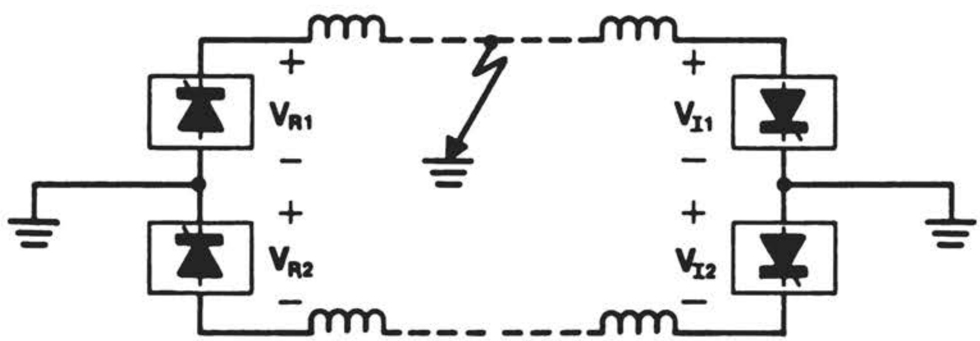

FIGURE 7 Line to ground fault on bipolar system.

except that the return path is through the ground. After a brief time for deionization, the positive pole is restarted and normal operation resumes.

In the event of a converter failure, a similar procedure can be followed. If the conductor is healthy, the two converters can be bypassed with closing switches and current flows in both conductors. (A low voltage dc circuit breaker is used in the ground path to transfer the ground current to the other pole conductor.) If overload capability is designed into the converter, the generating capacity can be carried over half of the dc system for a period of time. This, again, is an energy conservation measure (to be discussed in more detail later).

Availability

CIGRE Study Committee 14, DC Links, established Working Group 04 with the scope of collecting and publishing information on the operating experience of HVDC systems. These data are published biannually for review by the study committee (Knudsen et al., 1984). The data are comprehensive and cover both mercury arc and thyristor valve installations. Table 1 lists outage hours and number of events for thyristor valve systems in 1982.

An improving pattern of performance is shown in Figure 8 (Barhman, 1984), which illustrates forced and scheduled energy unavailability in thyristor valve stations. The data prior to 1979 are not statistically significant as there were relatively few thyristor valve systems in operation. Again, continuing improved performance will lead to increased energy conservation.

PROJECTED TRENDS AND APPLICATIONS

Although modern high voltage direct current power transmission is entering its fourth decade, in many areas the technology is still benefiting from learning curve effects. This section identifies recent and projected near-term improvements in equipment and in system applications.

Equipment Trends

A review of the entries in Table 1 gives an indication as to where manufacturers have been putting emphasis on improvements in equipment design.

TABLE 1 Forced Outage Data for Thyristor Valve Systems, 1982

Category	Hours	Events
AC and auxiliary equipment	71.0	44
Converter valves	110.2	32
Control and protection equipment	98.5	75
DC switchyard equipment	67.5	27
Operator error, other	48.8	18

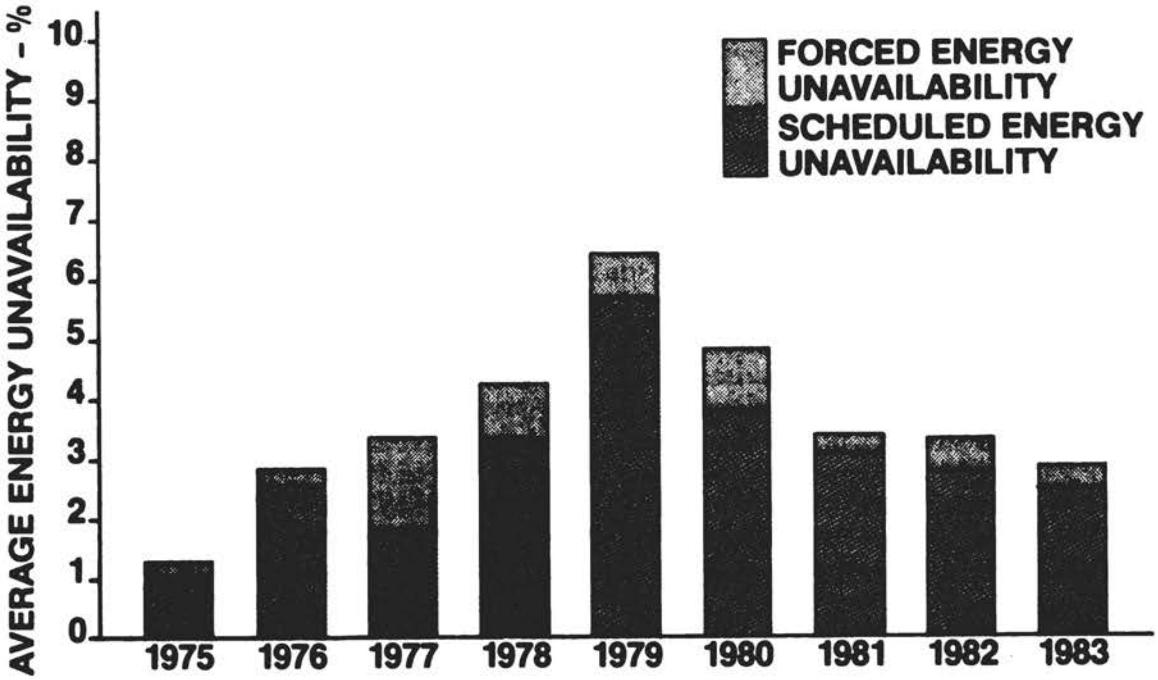

FIGURE 8 Average energy unavailability, thyristor valve stations.

AC and Auxiliary Equipment

Converter transformer failures have been a cause of some system outages. Transformer design is complex because primary windings are subjected to ac stresses while secondary windings see both ac and dc stresses. Improved valve design has resulted in lower transformer leakage reactances, a design simplification. Zinc oxide arresters now provide better overvoltage stress control.

Better knowledge of ac system harmonic impedance is leading to more efficient ac filter design, although further research is needed. Redundant auxiliary power supplies are utilized to ensure quick recovery from outages of adjacent ac systems.

Converter Valves

Improvements in the power handling capability of thyristors have had a major impact on HVDC transmission. Voltage and current ratings now can exceed 6 kV and 3.5 kA. Water cooling ensures protection against surge current overloads. Easy replacement of failed thyristors enables minimal forced outage time. A hanging valve design is beneficial in areas with seismic constraints.

Control and Protection Equipment

The extensive application of microprocessors has caused the conversion of many control and protection functions from hardware to software. Redundant microcircuits and error-checking algorithms lead to instantaneous switching from a faulty control signal to an accurate one continuously operating in parallel. Detailed factory check-out of controls on HVDC simulators (scaled hardware models) enables accurate control and protection settings prior to field installation. Changes upon installation and operation are achieved by software.

DC Equipment

Zinc oxide arresters with their much flatter voltage-current characteristics have improved the performance of equipment in the dc switchyard.

Operator Error, Other

The control and projection improvements mentioned above will reduce the incidence of operator-derived errors.

Losses, Costs

DC substation losses have seen significant reductions in recent years, principally because of improved thyristor designs. As thyristor voltage capabilities have improved, fewer series-connected thyristors have been required for a given voltage. Since a thyristor has a conduction voltage of approximately 1.25 V, fewer thyristors mean lower losses.

Also, as mentioned, the higher current capacity has led to reduced leakage reactance in the converter transformers. Lower winding resistance is thus achieved. Losses associated with the water cooling system are also lower than with previous air-cooled systems.

Overall, the losses at a dc converter terminal are now typically 0.7 percent of the full load dc power rating. This is down from about 1.5 percent in the mid-1970s.

Converter terminal costs have, interestingly, remained nearly constant since the late 1970s. The Square Butte project, commissioned in 1977, was constructed for $40/kW (Long and Lasseter, 1981). Cost data published at a conference sponsored by the U.S. Department of Energy, Division of Electric Energy Systems in 1980 (Molnar, 1980) can still be considered reliable. The "learning curve" has brought significant benefits in reducing losses (energy conservation, again) and in controlling equipment costs.

Applications

Several examples of near-term applications can illustrate new system-related developments in dc transmission.

Low Short Circuit Ratio Systems

When an ac receiving system is strong (i.e., stiff), the dc inverter will not interact significantly with it. However, if the ac system is weak (high impedance) with respect to the dc inverter, interactions between the two will occur. These are referred to as low short circuit ratio (SCR) systems, in which the short circuit ratio is defined as the ac short circuit MVA at the converter bus (minus ac filters and compensation) divided by the rated dc power of the converter. If the SCR is less than 2.5, these interactions are likely to occur.

The following system considerations must be accounted for in such applications:

1. stable regulation of active and reactive power,
2. ac system voltage regulation and stability,
3. overvoltage control and protection,
4. reliable recovery from disturbances without undue delay, and
5. commutation failure performance.

Presently under construction is the Highgate Converter Station, located in extreme northwestern Vermont near the Quebec-Vermont border. The converter station is adjacent to the existing Highgate Substation, fed from a 115-kV line. Hydro Quebec is constructing a 120 kV transmission line from their Bedford Substation to interconnect with the Vermont Electric Company system at the border.

The Highgate converters are rated at 200 MW with a full load direct current of 3600 A and a full load direct voltage of 565 kV. An overload capacity of 234 MW is available under certain conditions. To meet the maximum reactive power demand of the dc converters and the ac transmission, approximately 150 MVAR of shunt compensation is provided at each terminal. Shunt compensation consists of ac filters and capacitor banks arranged in nominally sized 10- and 20-MVAR individually switchable blocks. With reactive compensation required for the dc converters and also the ac transmission systems, the effective short circuit ratio (including compensation) at each side is about 1.6 at full load. Single contingency ac line outages reduce the effective short circuit ratio even more.

Specially designed equipment, control, and operating procedure features are necessary to enable the Highgate station to function acceptably under disturbance conditions. Radial ac line outages are an example of such a disturbance. If the ac line feeding the rectifier is tripped, load rejection would occur giving overvoltages on the inverter ac bus. Although firing the valves in the normal sequence keeps the reenergization overvoltages down, it does not keep the fundamental frequency overvoltages on the other commutating bus from rising. Blocking the rectifier with bypass pairs provides a path for direct current, allowing the inverter to temporarily operate as a rectifier until the ac reclosing sequence is successful. This action limits overvoltages by absorbing reactive power while awaiting restoration of commutating voltage.

A similar situation exists for outages of the line feeding the inverter but with the added complication of undesired commutation on the ac filter counter-voltages alone. Blocking the inverter with bypass pairs allows the rectifier to be used to absorb reactive power and suppress overvoltages on its commutating bus. Operation in this manner requires that the converters be capable of running at 90 degrees with normal commutation or in continuous bypass for the duration of the fault clearing sequence.

Overload Capability

The Intermountain Power Project (IPP) HVDC transmission system will transmit power from a coal-fired generating station in Utah to a converter station near Adelanto, California--just outside the Los Angeles basin. The system will be ± 500 kV, 1,600 MW; the length is approximately 500 miles.

A feature of the IPP system is the overload profile indicated in Figure 9. Arguments continue unabated as to whether a bipolar dc system is "equivalent" to a double circuit ac system. In this case, a pole outage can be accommodated by transmitting 2 per unit power over the other pole, then reducing the transmission to 1.5 per unit at a rate corresponding to generator output reduction. Generator tripping is avoided.

Multiterminal HVDC Systems

Existing point-to-point HVDC systems function well without dc circuit breakers. For clearing temporary faults (e.g., lightning-induced flashovers), a protection sequence is initiated that forces the line current to zero. After a brief pause (for deionization) the system is restarted. For parallel line switching, a similar sequence is followed whereby all switching is done during zero-current conditions. As multiterminal systems begin to receive consideration (Long et al., 1985), the need for dc circuit breakers becomes more of a concern. They may be of considerable benefit in these multiterminal systems in which a disturbance can propagate throughout the network. The strength of the ac system is an important factor here in determining what propagation effects occur. The ac system strength, in addition to the relation between it and dc converter power rating, will determine the acceptable speed of recovery of the dc system. Here the speed requirement for a dc breaker can be discussed--should it be able to outrace the controls? If so, opening speeds on the order of 5 ms will be required. If the breaker is to coordinate its action with the systems controls, a much slower device will be needed (of, perhaps, 30 ms). More will be said about dc circuit breakers in the final section of this paper.

The first true multiterminal system with geographically separated converters will be the Italy-Sardinia 200 MW undersea link. It is adding a parallel 50 MW tap on the island of Corsica, across which the existing link traverses. No dc breakers will be used. Control action will suffice for all normal and abnormal operating situations. In the case of an ac fault near the Corsica converter, the entire link will be shut down, then restarted without the tap. After attaining steady-rate operation, the Corsica tap will be restarted.

A second three-terminal system is under consideration in New England. A 670 MW system is now under construction connecting Quebec to central New Hampshire. An extension to central Massachusetts would increase the transmission capacity to 2,000 MW. A further expansion could occur in Quebec, where hydropower from the James Bay development could be brought by a 2,000 MW HVDC system to the Montreal area, there to interconnect with the 2,000 MW three-terminal system into New England.

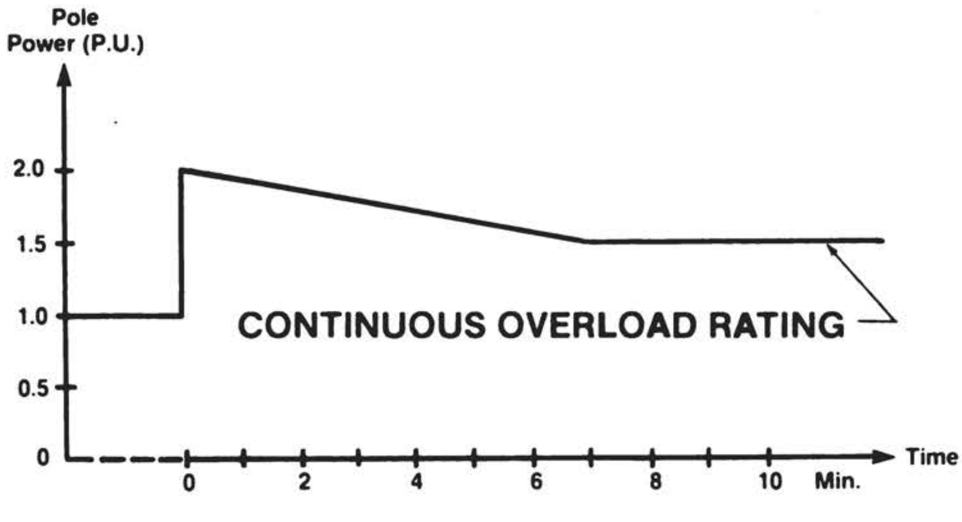

FIGURE 9 Intermountain Power Project overload capability.

A number of multiterminal options are possible on the West Coast, as indicated in Figure 10. The Pacific HVDC Intertie presently transmits 2,000 MW at ± 500 kV. Additional converter capacity is planned at Celilo (Oregon) and in Los Angeles, with 100 MW being added in parallel to the existing converters. The Intermountain Power Project previously mentioned is now under construction. A multiterminal system from Phoenix to Mead (Nevada) to Los Angeles is under study. The original Pacific HVDC Intertie plans included a second system between Celilo and Mead, and this is still a possibility. All of these systems will be at ± 500 kV; there certainly exists the potential for multidirectional coordinated energy exchanges. DC circuit breakers could be an essential element in such a network.

Urban Applications

HVDC power transmission has significant potential for urban applications where there are high load densities. This subject was the focus of a U.S. Department of Energy, Division of Electric Energy Systems (DOE/EES) symposium in 1983 (Biggs and Long, 1983). Important considerations are as follows:

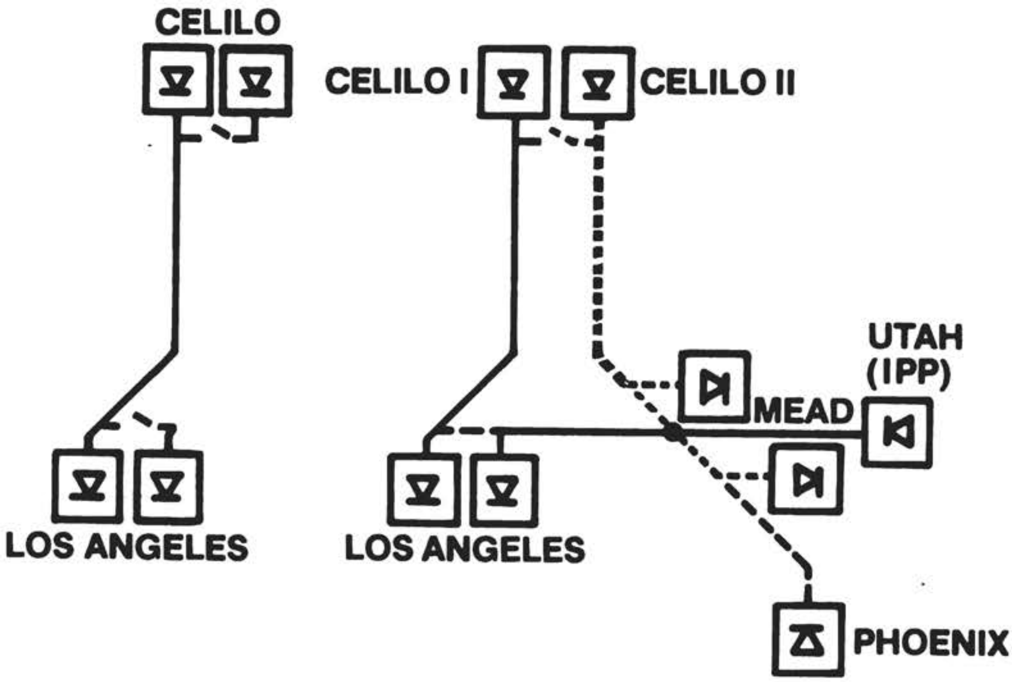

FIGURE 10 Possible West Coast HVDC networks.

1. Right-of-way restrictions--dc can deliver two to four times the power of an ac system over the same right-of-way. This is a key factor in accommodating urban load growth in congested areas.

2. Controlled flow of current--dc can control the current injected into the receiving ac system, including multiple injections into different locations. This can be advantageous compared to ac, where cable impedances control the routing and overload limits are restrictive.

3. Voltage control--converters can, by firing angle control, assist in controlling ac system voltages. This can be especially helpful in recovering from disturbances.

4. Security--the combination of routing current flow, voltage control, and overload can lead to more secure (robust) networks, minimizing the potential for cascading urban outages.

5. Converter station size--compaction of dc converters will be necessary to accommodate the expensive and/or limited real estate conditions found in urban areas.

While some studies of urban applications of dc systems have been conducted, the potential is as yet unrealized. Activity in this area is expected in the 1990s.

RECOMMENDED RESEARCH ACTIVITIES

Research in electric power transmission systems is presently conducted and/or sponsored by four different groups or organizations:

1. Electric utilities--they conduct/sponsor research pertinent to their specific needs, usually (but not always) near term. American Electric Power's research into UHV transmission and Southern California Edison's research into alternative sources of energy are two well-known examples.
2. Manufacturers--they conduct research intended to provide them with a competitive edge in the marketplace. Advances in power semiconductors are an example.
3. Electric Power Research Institute (EPRI)--EPRI sponsors research of near-term (typically up to five years) interest to the electric utilities, who provide the funding.
4. U.S. Department of Energy, Division of Electric Energy Systems--DOE/EES sponsors research of a longer term (typically five to ten years) interest to the utility industry.

Three areas of research activity are proposed as suitable for DOE/EES support: equipment, system studies, and education. These are described in the following sections.

Equipment Research

Manufacturers are actively involved in equipment research, but there are speculative areas in which DOE/EES support would be appropriate.

Direct Current Circuit Breakers

Interruption of direct current at high voltage is technically difficult as there is no naturally occurring current zero to aid in the interruption process. Recent field tests have been conducted (Vithayathil et al., 1985) on two laboratory prototypes. Both of these were limited in speed of operation (two to three cycles) and current rating (1.1 per unit interrupting capability) and required assistance from system controls. The advantages achievable from multiterminal configurations are such that advanced dc circuit breakers could hasten their development. The following specific areas of research are recommended:

1. Reliability--field data from an actual application (e.g., parallel line switching) could complement laboratory data, where sufficient energies are not available.

2. Current capacity--higher current interruption capability is needed.

3. Speed--faster operation (less than five milliseconds) may have advantages for certain applications, such as isolating a major disturbance.

4. Control and protection--the operation (or nonoperation) of the breaker must be coordinated with the system control and protection. Examples are identifying where a fault has occurred in a meshed network, and discriminating between a fault and a commutation failure.

Forced Commutation Circuits

Present dc converter circuits are line commutated; that is, a preexisting ac voltage is required for current transfer from valve to valve. Forced commutated converter circuits appear to have advantages, especially in low short circuit ratio applications. The following specific research areas are recommended:

1. New bridge configurations--an alternative bridge circuit could be installed in parallel with an existing bridge in an operational station to examine normal operating and failure modes and (especially) reactive power control.

2. New power semiconductors--gate turn-off devices (GTOs) have the capability of operating beyond the normal firing angle limits. Research into GTOs should examine improved voltage and current ratings, efficiency, and failure modes.

System Studies

There are two areas in which system studies sponsored by DOE/EES would be appropriate.

Multiterminal HVDC Systems

These studies need to be coordinated with the previously mentioned dc circuit breaker research. Detailed investigations into actual applications of multiterminal systems can indicate where dc breakers are needed and what their ratings must be. Control and protection should be studied, with special attention paid to coordination of the dc system with the associated ac systems.

Improved Utilization of AC/DC Systems

1. Coordinated operation of ac/dc systems--because of the controllable routing of dc current, better utilization of an integrated ac/dc network could be achieved. Overall efficiency can be improved if inadvertent flows are limited. This applies to large networks (e.g., the "western donut") or to urban cable systems. System security can be enhanced by the dynamic control of active and reactive power. The timely mitigation of major disturbances can lead to more robust systems, reducing the likelihood of cascading outages.

2. Urban applications--this would expand on the coordinated operation of ac/dc systems with particular application to urban systems and cable overloading.

3. Bulk energy transfers--interregional energy transfers can be more efficiently enabled if transmission bottlenecks can be minimized. Not only can oil displacement occur (energy conservation, again), but protection is available against natural catastrophes or human events (e.g., coal strikes).

Education

DOE/EES has sponsored two recent symposia on HVDC transmission. The first, "Incorporating HVDC Power Transmission into System Planning," was held in 1980 in Phoenix, Arizona, and attracted a large audience. It can be suggested that the expansion of dc systems in the western United States (Figures 1 and 10) was encouraged by the information presented at this symposium.

The second symposium, "Urban Applications of HVDC Power Transmission," was held in 1983 in Philadelphia, Pennsylvania. It coincided with the conclusion of a DOE/EES sponsored study by Philadelphia Electric Company, which investigated bringing large blocks of dc power into downtown Philadelphia. The audience was modest in size, indicating that urban applications of HVDC systems are not likely until well into the next decade.

Because dc technology is not as well understood as ac technology, it is recommended that DOE/EES actively support education through symposia, workshops, and publications relating to ongoing research activities.

CONCLUSION

High voltage direct current power transmission is, appropriately, a conservative technology in spite of its recent emergence. It enables the conservation of electric energy through efficient and reliable operation, in coordination with the associated ac systems. Proper coordination of DOE/EES research support with the research activities of other organizations can provide a conservation of financial resources as well. The result will be a secure and economical electric energy transmission network.

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ELECTRIC LOAD LEVELING AND ENERGY MANAGEMENT

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INTRODUCTION

For more than a decade, the Electric Power Research Institute (EPRI) and the Federal Government have been supporting a number of important programs aimed at the development of advanced technologies for leveling and otherwise managing the time-variable loads experienced by electric utilities. These programs continue to be motivated by two considerations, (1) the expectation of very significant economic and operating benefits from achieving a better match between the cyclic demands of utility customers and the desired constant output of a utility's base load plants, and (2) the general lack of technical options for achieving an improved match. During this period, significant technical progress has been made in private sector and Government R&D programs, and several load-leveling and energy management technologies have moved closer toward practical applications. While these programs evolved, important changes have been occurring in almost every aspect of electric utility operations and environment. Given these changes, it is appropriate and timely to ask whether and to which extent support of research, development, and demonstration projects in this area is still appropriate. The key questions would appear to be:

- Has the need for new load-leveling and energy management technologies changed as a result of reduced and uncertain load growth, cancellations of plans for generating capacity additions, impacts of conservation and load management programs, shifts in economic activity, and changes in societal energy use patterns?
- Are the load-leveling and energy management technologies targeted for development years ago still responsive to current needs?
- To what extent have these development programs been successful?
- What roles can private-sector and Federal R&D programs play in assuring the development and introduction of useful load-leveling and energy management technologies?

This paper attempts to develop some answers to these questions by examining what is happening to utility loads; how new technologies might be used to more effectively level and manage these loads; and when, on the basis of R&D progress achieved to date, viable technical options for load leveling and energy management might become available to utilities and their customers.

The demand for electric power is determined by the instantaneous needs of electric users. As shown in Figure 1, these needs follow distinct periodic patterns: the basic daily cycle of most individual and societal activities, a weekly cycle that reflects reduced economic activity on weekends, and an annual cycle caused by seasonal (primarily weather-sensitive) loads. On the other hand, electricity is supplied most economically and reliably as the constant output of large coal and nuclear base load power plants.

As is well known, electric utilities approach the problem of matching daily and weekly demand variations by operating not only base load but also intermediate cycling and peaking plants of various types. These generally represent the most economic compromise between capital and operating costs for shorter periods of operation. Also, most utilities take advantage of seasonal load variations by scheduling plant maintenance and refueling operations during periods of low demand.

Many if not most of the complexities and inefficiencies in the operation of electric power systems are derived from the requirement to meet time-variable demands instantaneously and with high reliability. Moreover, the economic penalties of this strategy have become increasingly severe as capital costs of all types of power plants and the costs of peaking fuels have increased over the levels experienced when "generation mix" strategies were first adopted by utilities. In response, many utilities are now making efforts to more actively manage their demand rather than simply meeting it. As is evident from Figure 2, however, the aggregate annual load factor* of U.S. utilities has not improved and is not expected to do so over the forseeable future. One may conclude that utility efforts to improve daily load shapes and annual load factors are being offset by long-run trends toward the "service economy" and growing personal prosperity: growth in the inherently more cyclic commercial and residential electricity consumption is outstripping industrial load growth.

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*While the annual load factor (ALF) is a direct measure only of demand variations over an annual cycle, trends in ALF reflect the same trends in daily and weekly load factors.

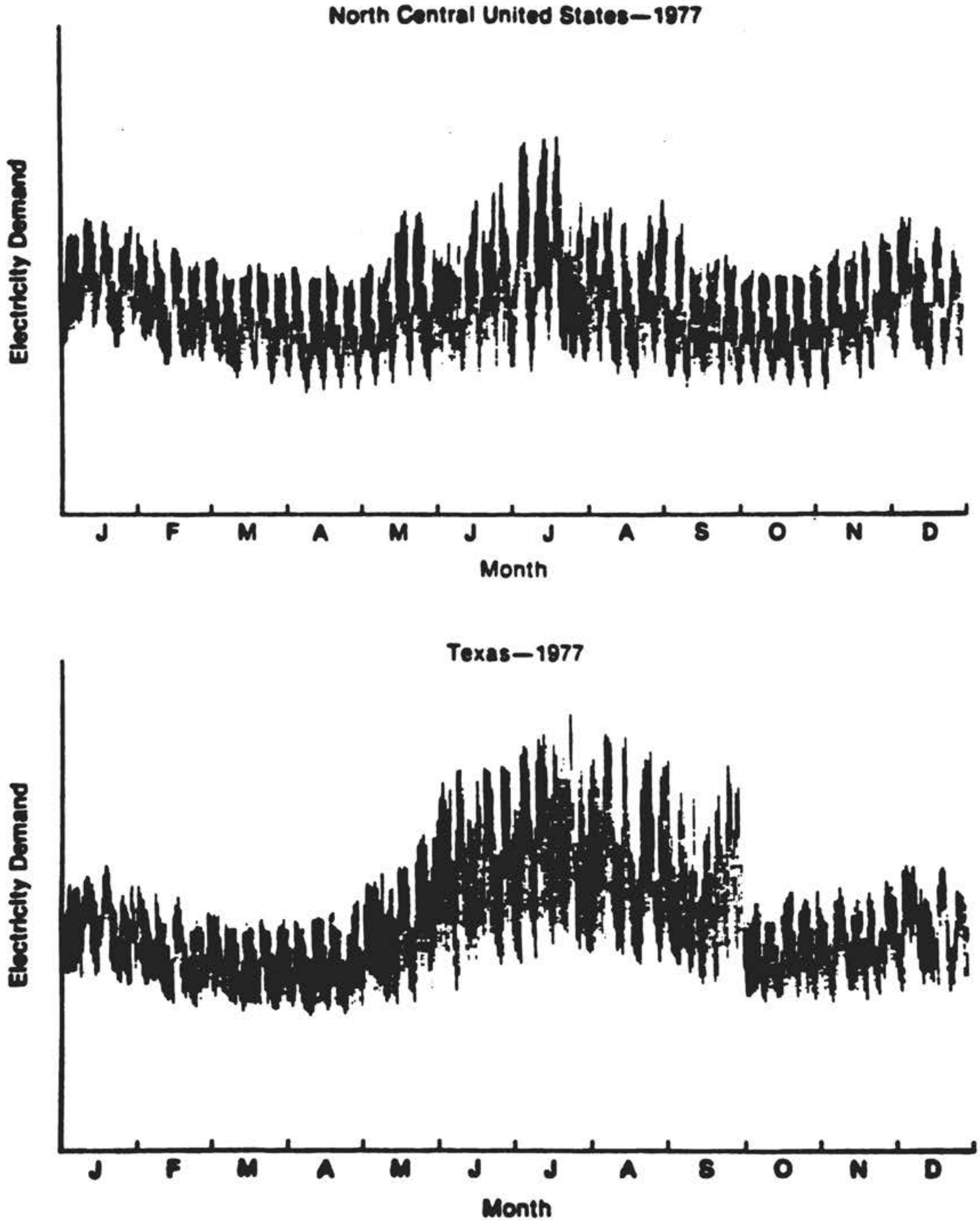

FIGURE 1 Annual load curves for utilities in two regions of the United States.

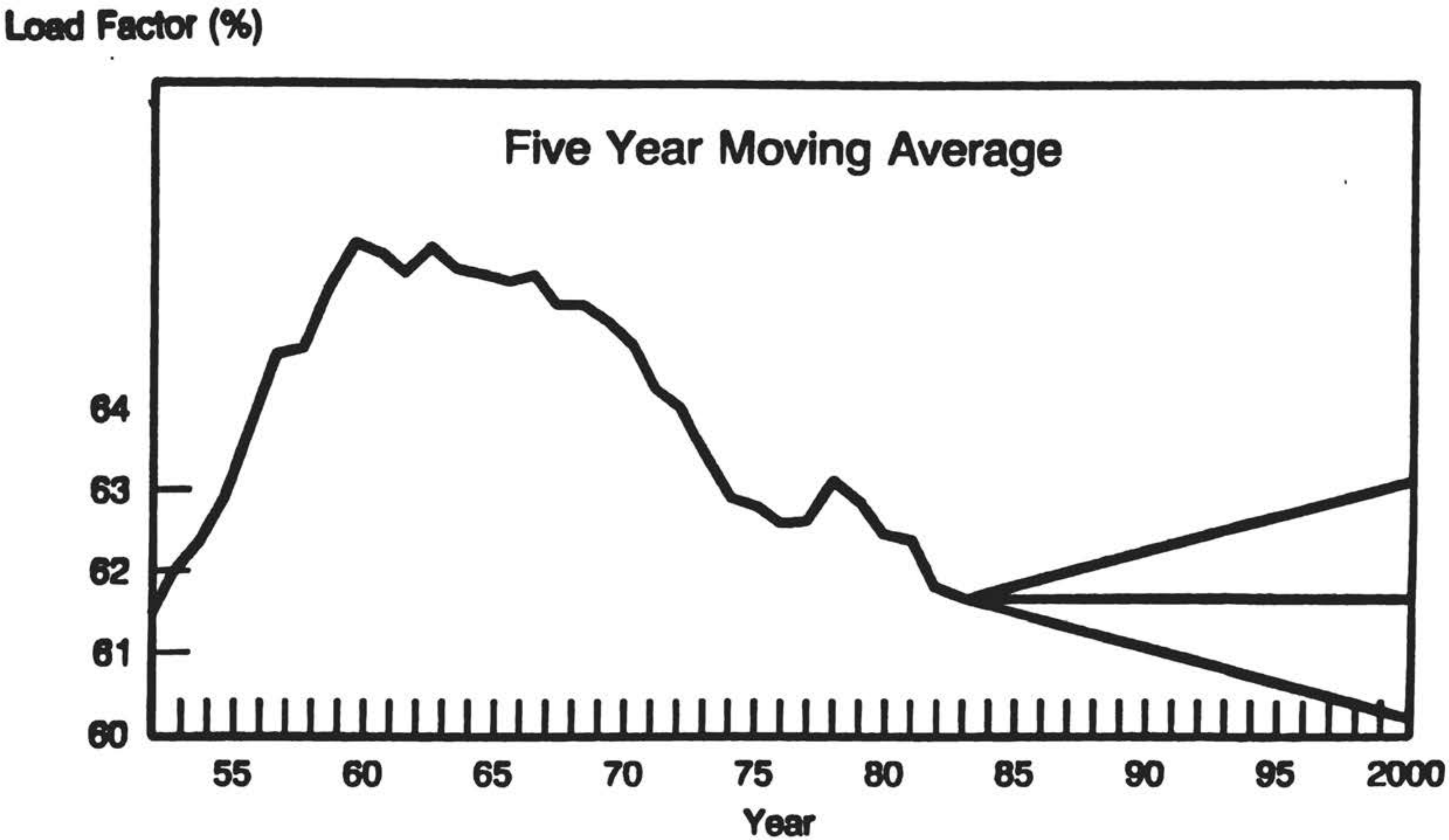

FIGURE 2 Annual load factors.

One serious consequence of poor load factors is that the utilization of coal power plants, expressed by their aggregate capacity factor (see Figure 3), is generally less than their availability (current national average 72 percent). Moreover, this situation is likely to get worse in view of the fact that coal and nuclear base load plants will make up 85 percent of the capacity additions over the next 10 years (see Figure 4). Thus, there is already a large economic incentive to level the loads that must be served by electric power plants in this country. It seems clear that the economic incentives for load leveling will be growing further under the combined impacts of (1) the rising costs of utility investments in base load plants, (2) socio-economic trends that tend to shift electricity use patterns toward lower load factors, and in the longer term, (3) increased cost as well as reduced availability of peaking fuels.

UTILITY STRATEGIES FOR LOAD LEVELING

One major strategy a utility* can consider for leveling the load seen by its generation (and, also, transmission) is to store energy on the electric power system: under full control of the utility, storage is used to effectively shift load from times of high demand to off-peak periods. Such a strategy is attractive if low-cost base load electricity is available as can be predicted for many parts of the United States over the next 10-15 years, if sufficiently inexpensive and efficient energy storage systems are available, and if energy storage offers operating characteristics comparable or superior to cycling and peaking generation.

Pumped hydro, first introduced more than 50 years ago, has met these criteria for several regions of the country, and more than 13,000 MW of pumped hydro capacity have been installed on U.S. utilities. This represents about 3 percent of generating capacity, or about 25-30 percent of the capacity that could be deployed in the form of energy storage for load leveling, assuming present base load capacity factors and competitive costs of storage installations. Furthermore, the excellent dynamic response of pumped hydro plants provides economic incentives for installing more pumped hydro capacity than would be justified by the peak-shifting duty alone. Indeed, several U.S. utilities derive well over 10 percent of their total capacity from pumped storage. In Japan, this type of storage provides 10 percent of capacity, much of which is used for dynamic duty and system reliability, and Figure 5 illustrates how pumped storage is used in the United Kingdom to respond to sudden load increases. As a utility's inventory of power plants is shifting to more and older base load

*For the purpose of this discussion, the term "utility" means an individual utility company, a power pool, or any other aggregation of utilities that shares generation resources.

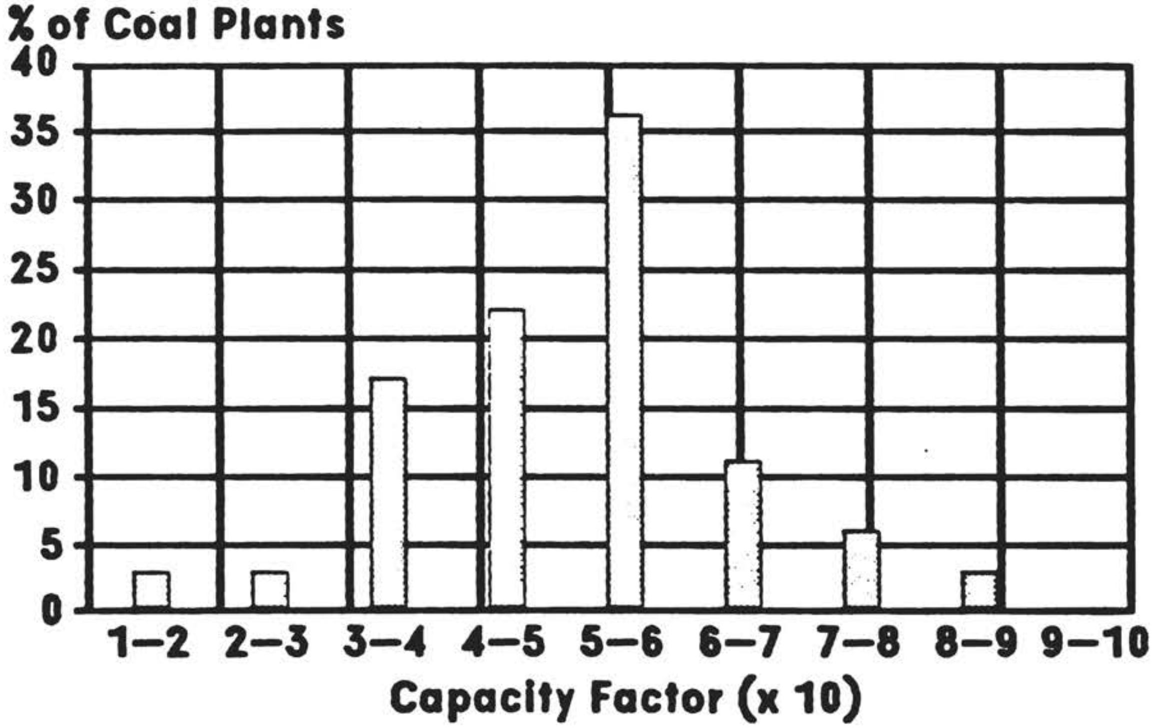

FIGURE 3 Capacity factor of coal plants in the United States--1982. Average capacity factor = 45 percent.

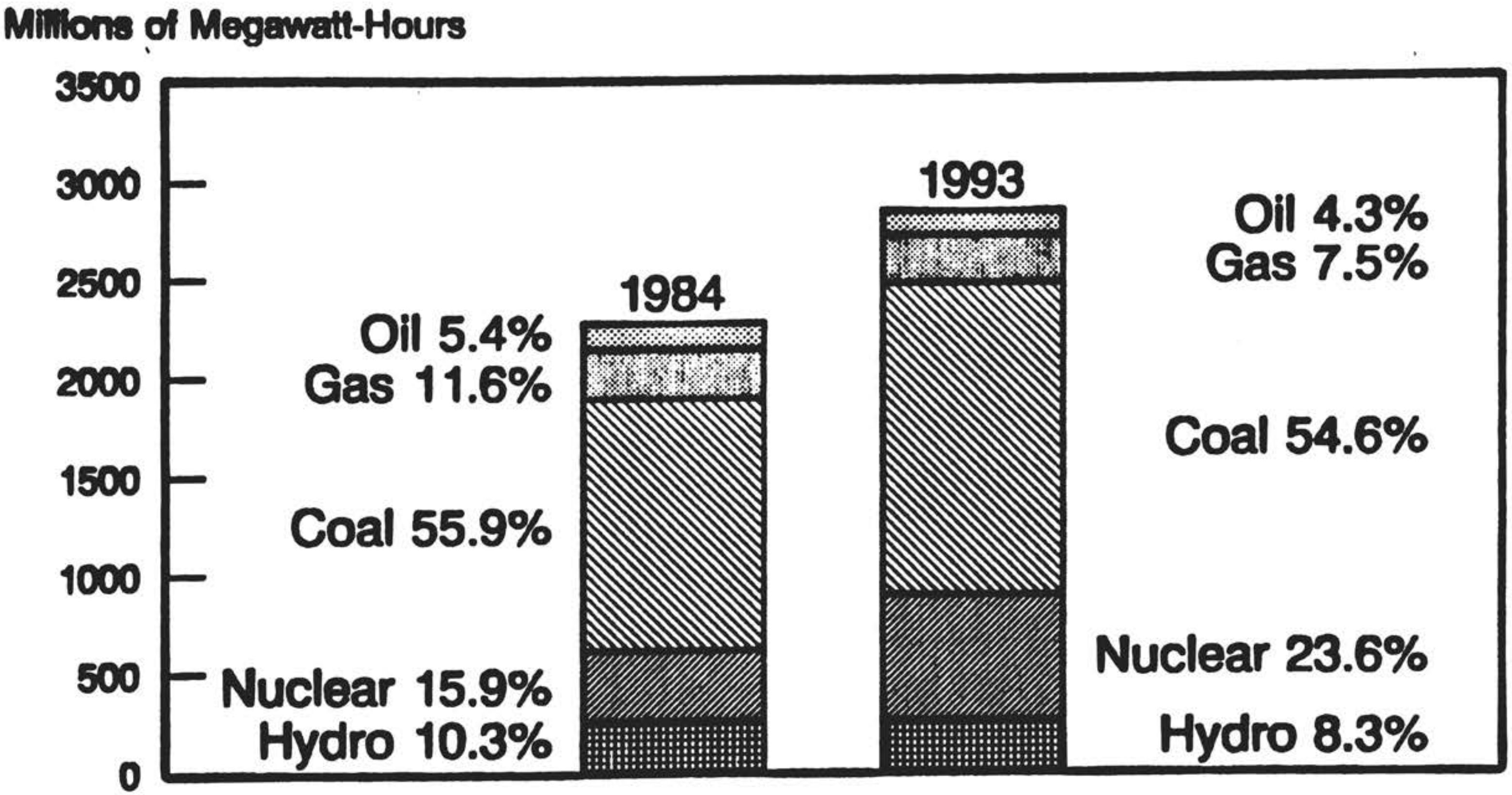

FIGURE 4 United States electricity generation by fuel (NERC).

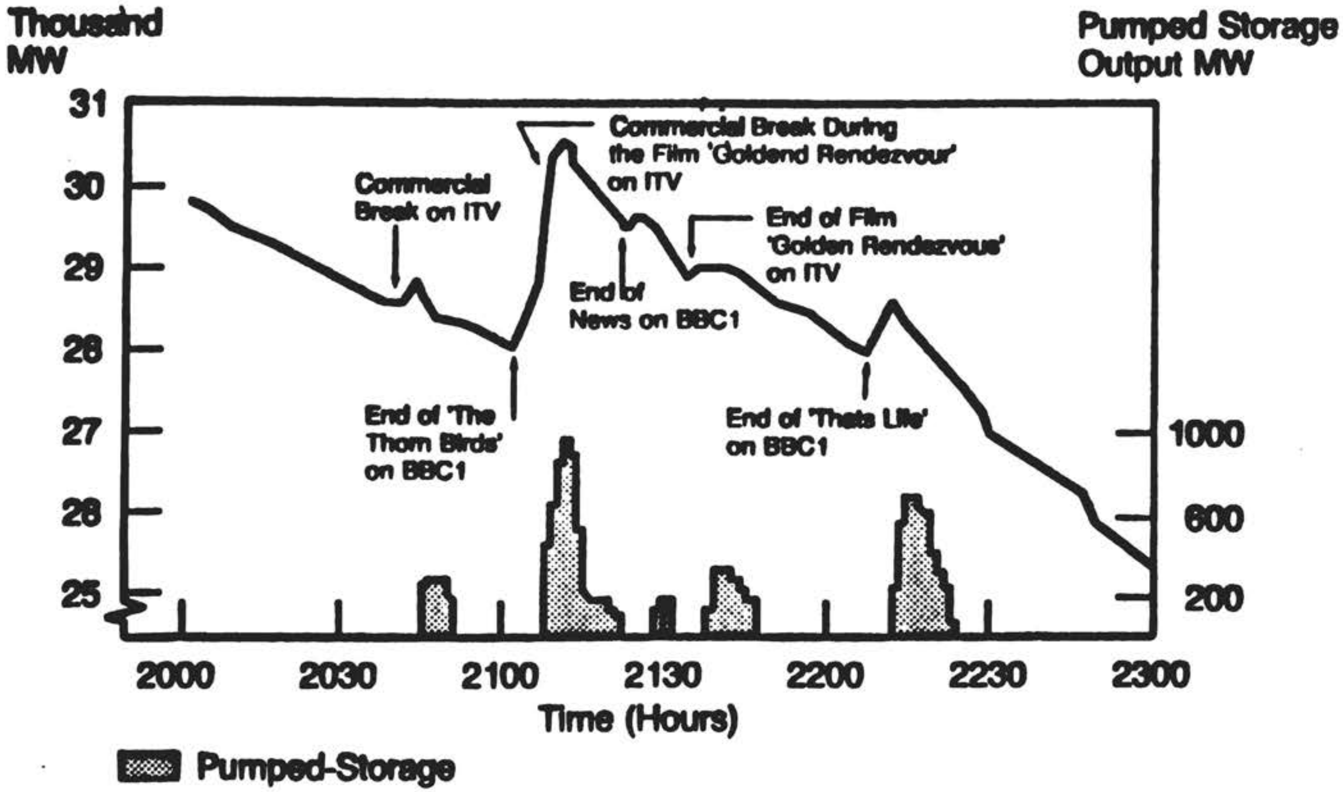

FIGURE 5 Demand curve for the evening of Sunday, January 22, 1984, when "The Thorn Birds" on BBC1 caused a demand increase of 2,600 MW at 2107 hours.

plants for which cycling is both uneconomical and detrimental to reliability, the value of this dynamic response capability will be increasing.

With the addition of about 7000 MW currently under construction or planned, pumped hydro capacity will remain at less than half of the total U.S. potential for utility energy storage installations. The limited availability of sites with suitable topology and geology is one factor preventing wider use of pumped hydro; other important barriers are continuing concerns about its environmental impacts and the unwillingness of utilities to become involved in the large, long-term, and costly projects typical for pumped hydro. It was the limited prospects of pumped hydro vis-a-vis the substantial potential for utility system energy storage that resulted in the emergence a decade ago of significant efforts to develop alternative methods of energy storage.

While storage technologies such as underground pumped hydro, batteries, flywheels, compressed-air storage, heat storage systems, superconducting magnetic energy storage, and other concepts were being explored and developed in federally and privately funded R&D programs, the management of customers' demand for electricity--as opposed to management of electricity supply--began to emerge more clearly as a second major strategy for leveling the aggregate load seen by a utility's generation. Current expectations are that this "demand-side management" (DSM) strategy will have significant, favorable impacts on utility load curves. If borne out in the future,* DSM conceivably could begin to affect the extent as well as the type of load-leveling energy storage which utilities might wish to deploy themselves or encourage their customers to install. Clearly, this possibility needs to be considered explicitly in Federal and private-sector programs to develop and commercialize energy storage technology intended for load-leveling applications.

Figure 6 shows schematically in which ways DSM could have an impact on utility load curves. Strategic conservation and growth designate measures to decrease and increase, respectively, system load, in each case with the intended result that energy costs decrease as a consequence. Examples of strategic conservation include better insulation of buildings and more efficient lighting where such measures, in the aggregate, can help eliminate or defer the need for construction of new power plants. Electricity-intensive but productivity-enchancing manufacturing processes such as laser cutting, microwave drying, use of plasma in steel making, etc., are examples of strategically desirable load growth if these new uses of electricity can be served by already available or committed generating capacity. Conservation and growth DSM strategies primarily influence demand for energy (kWh) rather than power (kW of peak demand).

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*While DSM may in fact have already had some favorable impacts, these may have become obscured by opposing factors, see page 2.

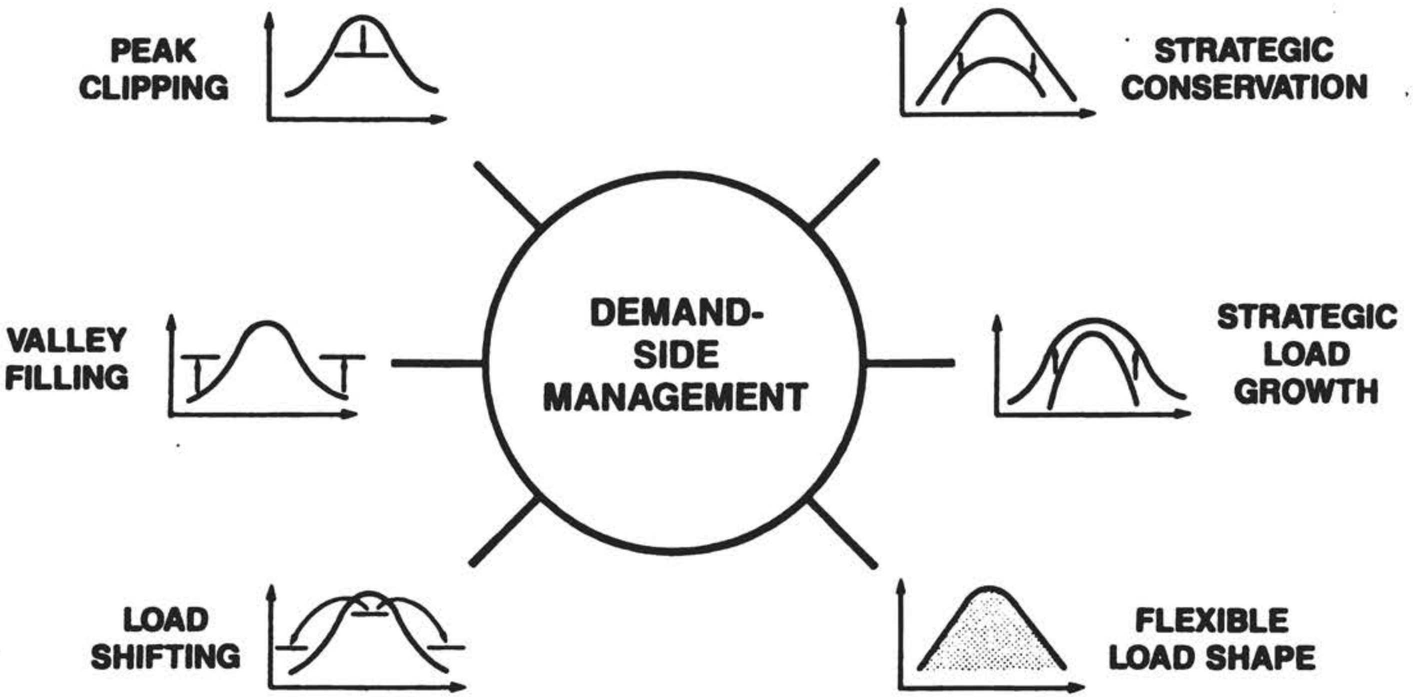

FIGURE 6 Demand side options.

Of more direct impact on load shapes and, thus, on the need for load leveling are the DSM strategies noted in the bottom half of Figure 6. Peak clipping, exemplified by utility-controlled cycling of electric air conditioning, is a strategy aimed at reducing peak demand during the normally rather few days of a year when demand threatens to exceed a utility's capacity to serve. Its impact on annual or even daily load factors is relatively small and generally less than estimated because much of the cooling load tends to be recovered still on peak through a temporary increase in the duty cycle of naturally cycling air conditioning systems.

Valley filling can be brought about by introducing new electric loads that only operate during daily, weekly, or seasonal periods of low demand. The add-on heat pump, presently promoted by a number of utilities, is a valley-filling seasonal load, as is the heat storage furnace wherever it replaces oil or gas heat. The electric vehicle could become a year-round load filling night-time valleys. This could become interesting especially for urban utilities, many of which have poor load factors. Together, these three strategies could well have a significant impact on load factors in the longer run; note that two of these involve energy storage.

In principle, load shifting could be a particularly effective technique to level loads inasmuch as it reduces peak demands and fills off-peak valleys. Since it is generally not feasible to shift electricity-consuming activities from peak to off-peak periods on a large scale, load shifting requires some form of energy storage. Storage water heaters, controlled by time clocks or directly by signals from utilities, have been used for many years to shift the water heating load to off-peak periods. However, because of the limited amount of energy involved, the impact of storage water heaters on utility load curves is small. In recent years, electric space heating and cooling have become targets for load shifting. As shown in Figure 7, residential space heating and commercial air conditioning tend to be the largest contributors to winter and summer peaks, respectively. This has resulted in the current focus on development and introduction of residential storage heaters and of cool storage systems for commercial buildings.

Studies supported by EPRI indicate a substantial market potential for both of these demand-side load shifting techniques. Because of the amount of electricity involved, their extensive penetration could result in a significant leveling effect on utility load curves. However, their full impact is likely to develop only slowly: for heat storage, because neither rate structures to provide customer incentives for choosing this heating option nor sufficiently cost-competitive technology exist at this time; for cool storage, because current technology is not suitable for retrofit and thus is restricted to the much smaller market for new buildings (see Figure 8). Ongoing efforts to develop storage heaters and advanced cool storage systems suitable for retrofit aim to expand availability of cost-effective DSM options, but their impacts over the next 10-15 years are likely to be modest.

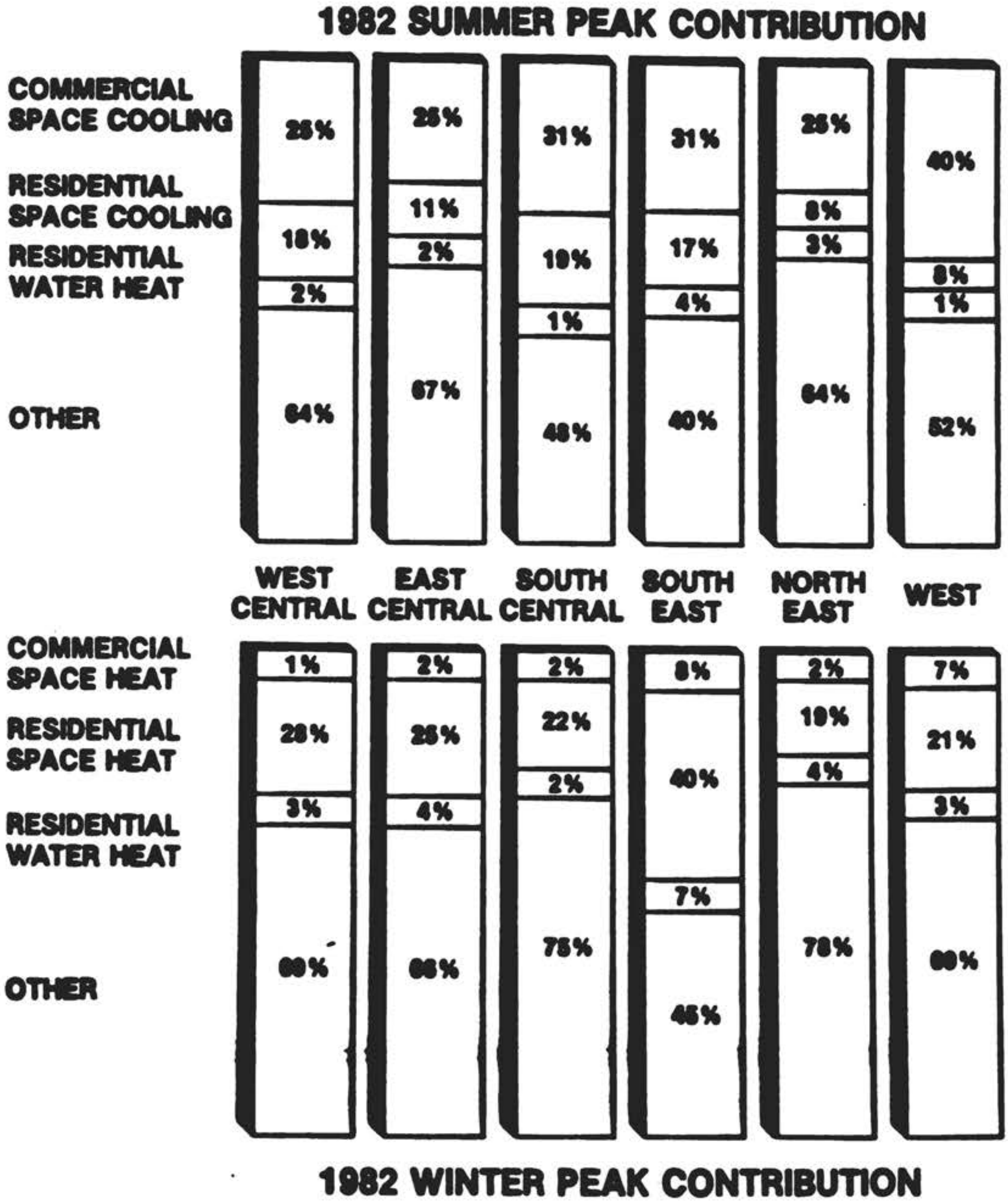

FIGURE 7 The contributions of electric heating and cooling to seasonal peak demands vary by region.

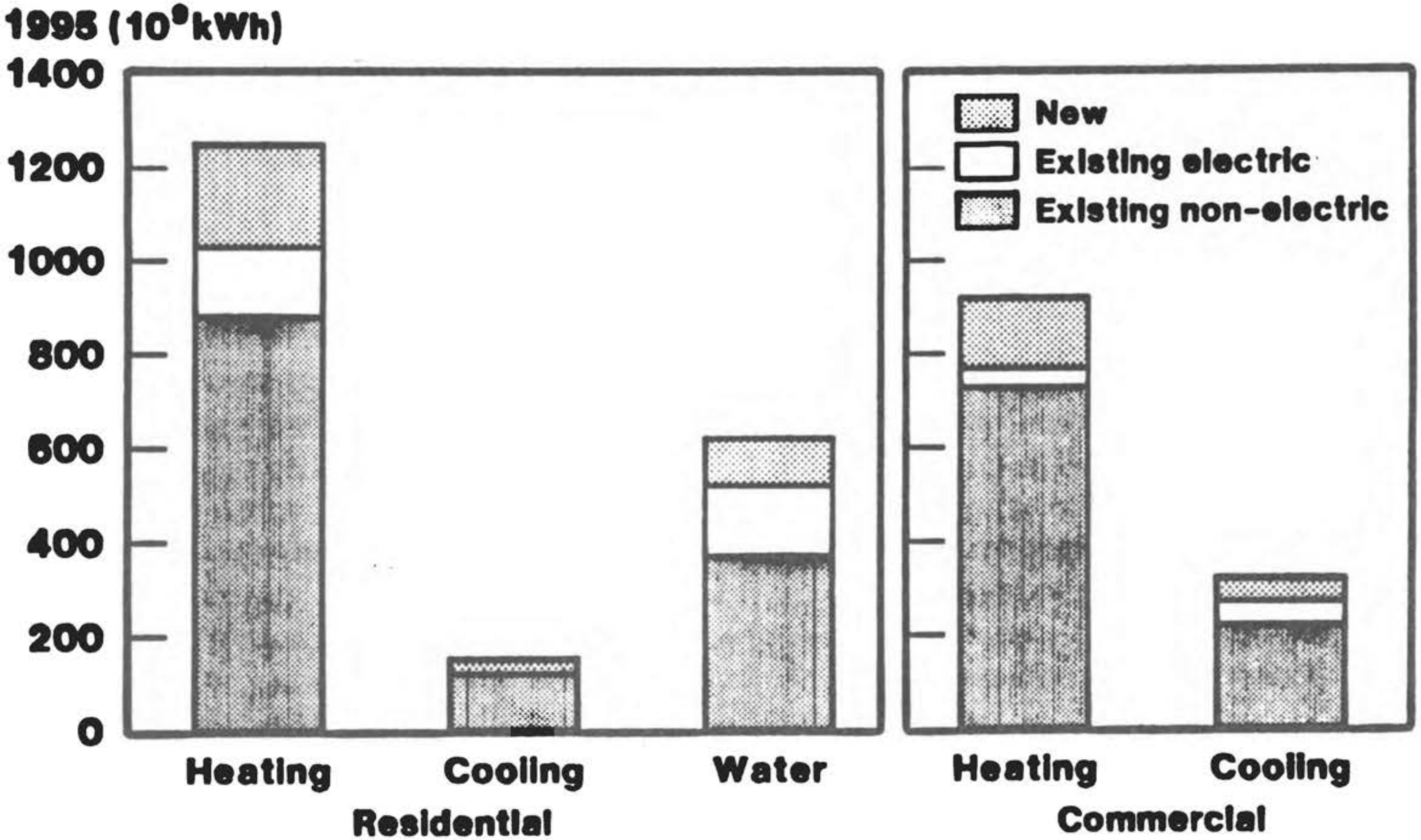

FIGURE 8 National market relative sizes.

While more detailed analyses of prospective DSM impacts clearly are needed, several conclusions of importance to private sector and federal energy R&D programs can be drawn from the foregoing:

1. The applications of pumped hydro storage are limited, and the full benefits of utility energy storage for load leveling can only be achieved through development and deployment of more broadly applicable storage options.

2. Current and forseeable implementations of DSM options are not likely to materially improve the load shapes and load factors of U.S. utilities during the remainder of the century.* Deployment of cost-effective energy storage systems by utilities thus will have significant economic and operating benefits.

3. While the full-load leveling potential from deployment of heat and cool storage technology in residential and commercial buildings will be realized only after technologies of reduced cost and broader applicability (including retrofit) are developed, significant utility and customer benefits can nevertheless be expected from their beginning deployment.

ENERGY STORAGE: TECHNOLOGY OPTIONS AND STATUS

The following discussion is focussed primarily on technologies for utility energy storage. The great diversity (technically and with respect to application) of these technologies and the complex technological challenges surrounding their development have resulted in large R&D efforts to ensure their ultimate use. No effort is made here to describe these options and their development issues in great detail; for this, the reader is referred to a number of pertinent technical papers, reports, and program documents given in the Appendix.

In the more than ten-year search for broadly applicable alternatives to pumped hydro, a long list of candidate technologies has been considered. Most candidates were eliminated on the basis of unacceptably high capital costs; but a number of them were explored at least to some extent. Figure 10 shows those that emerged from scrutiny with reasonable prospects to compete with pumped hydro or with generating equipment for cycling and/or peaking duty. Several of these technologies have been developed to the point where their first commercial application during the next five years can be envisioned.

In Figure 11, the capital cost characteristics of the leading candidates for utility energy storage are plotted. The figure illustrates that energy storage systems can be characterized by two largely independent cost parameters: the cost of the power-related components (generally, the energy conversion subsystems; for pumped

*See also Figure 9 which is taken from an unfinished EPRI study.

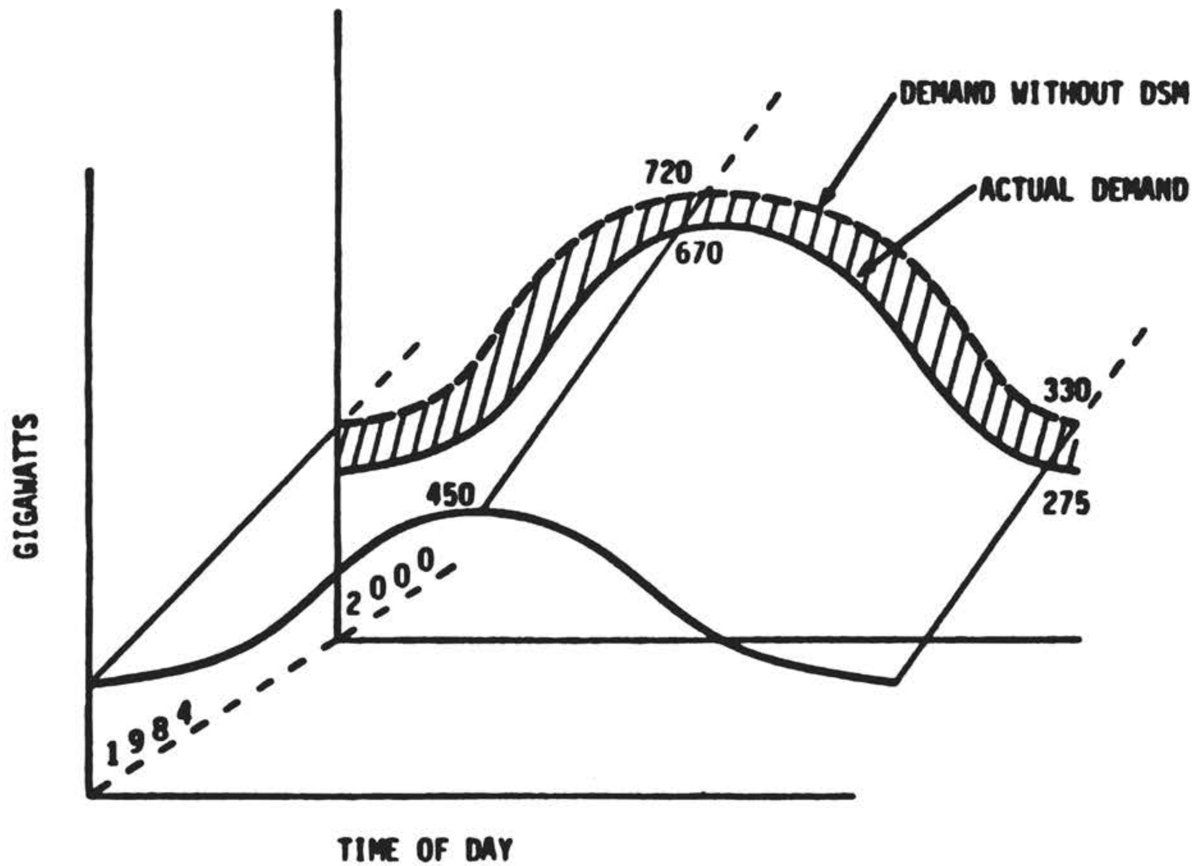

FIGURE 9 Demand and energy impacts will result from future load shape changes brought about by DSM.

TECHNOLOGY	CAPITAL COST POWER-RELATED ($/KW)	CAPITAL COST ENERGY-RELATED ($/KWH)	EFFICIENCY %	UNIT SIZE (MW)	LIFE (YRS)
PUMPED HYDRO	500	10	70	400-1500	50
UNDERGROUND PUMPED HYDRO	500	30	70	1000-2000	50
COMPRESSED AIR ENERGY STORAGE	490	10	*	25-220	35
BATTERIES					
LEAD ACID	100	140	75	5-20	10
ADVANCED	100	100	70	2-10	15
SUPERCONDUCTING MAGNETIC ENERGY STORAGE	200	200	91	1000-2000	40

*1 KWHR OF GENERATION REQUIRES .72 KWHR OF ELECTRICITY PLUS 4000 BTU OF GAS OR OIL

FIGURE 10 Energy storage technologies.

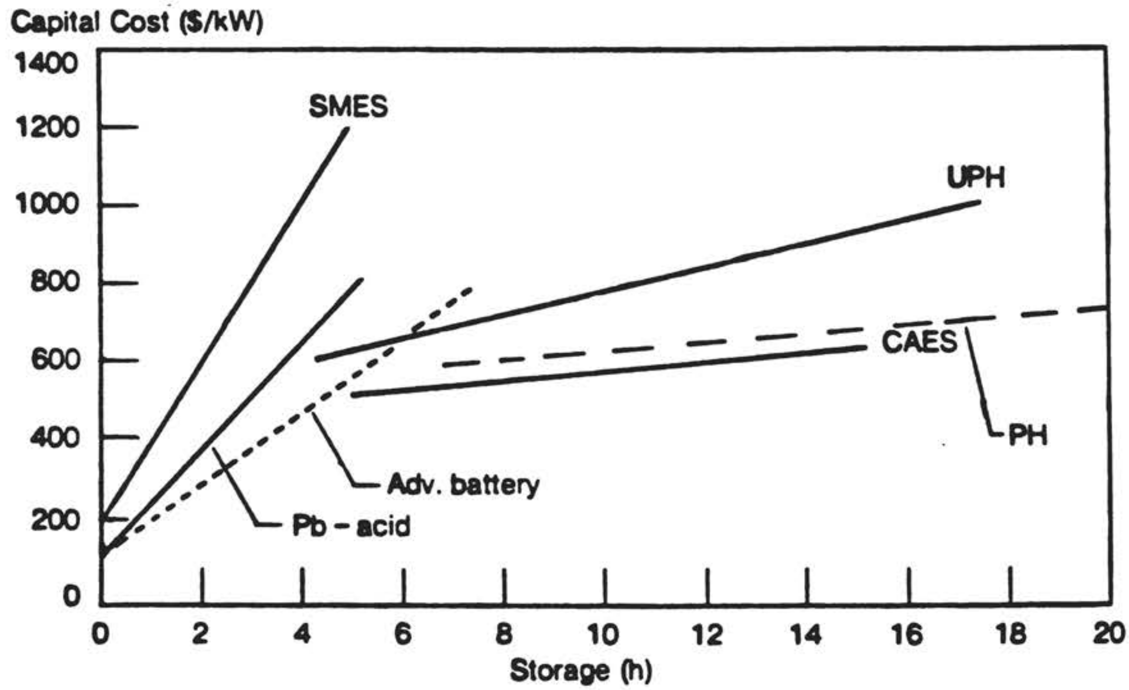

FIGURE 11 Capital costs (energy storage).

hydro, primarily the turbomachinery and penstocks), and the cost of the energy storage subsystem (e.g., the reservoir). Among the energy storage options shown in Figure 11, technologies such as pumped hydro and compressed-air energy storage (CAES) are relatively expensive with respect to their power capability (maximum rate of energy conversion). However, they are characterized by rather low costs per unit of storage: it is rather inexpensive to store water or compressed air in large amounts. On the other hand, battery systems will cost considerably more per unit of storage (that is, for the battery itself), but their power-related subsystem (primarily the AC/DC conversion system) can be rather low in cost. A similar statement applies to the storage of energy as permanent currents in the superconducting coils of electromagnets (SMES).

This leads to a logical distinction in the applications of these techniques: Pumped hydro and CAES are best used where storage systems must be capable of being discharged at rated power over longer periods, including combined daily and weekly cycles. Batteries and SMES, on the other hand, are more economical for shorter discharge periods, e.g. 5 hours per day or less. Together with their rapid electric response, this cost characteristic predestines batteries and SMES for spinning reserve, load following, and regulation duties, in addition to the leveling of shorter peaks. The screening curves of Figure 12 show this distinction for batteries and CAES. They also delineate the annual operating regimes in which the currently most promising energy storage options compete most readily with conventional peaking and cycling generation. It is apparent from Figure 12 that a "storage mix" is likely to be more economical than any single storage option by itself. This is one major argument for the development of more than one storage technology.

Which of these new energy storage technologies will actually be deployed and successfully operated on electric power systems--and when this will happen--is not yet clear. However, the discussion below of the main candidates and their development status suggests that this might well occur during the 1980s.

Underground Pumped Hydro (UPH)

In this variant of pumped hydro storage, the lower water storage reservoir would be created through excavation of a suitably shaped cavern in hard rock of adequate strength and integrity. An extensive design study carried out several years ago by a utility-AE team with DOE and EPRI funding concluded that UPH is technically feasible and likely to encounter fewer geological, topological, and environmental siting constraints than conventional pumped hydro. Plant costs, although higher than for conventional pumped hydro, are likely to be less than $1000/kW* which could be economically competitive. To

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*Cost of the 2000-MW plant designed in the referenced study was $600/kW (1979 dollars) including contingency but excluding interest during construction.

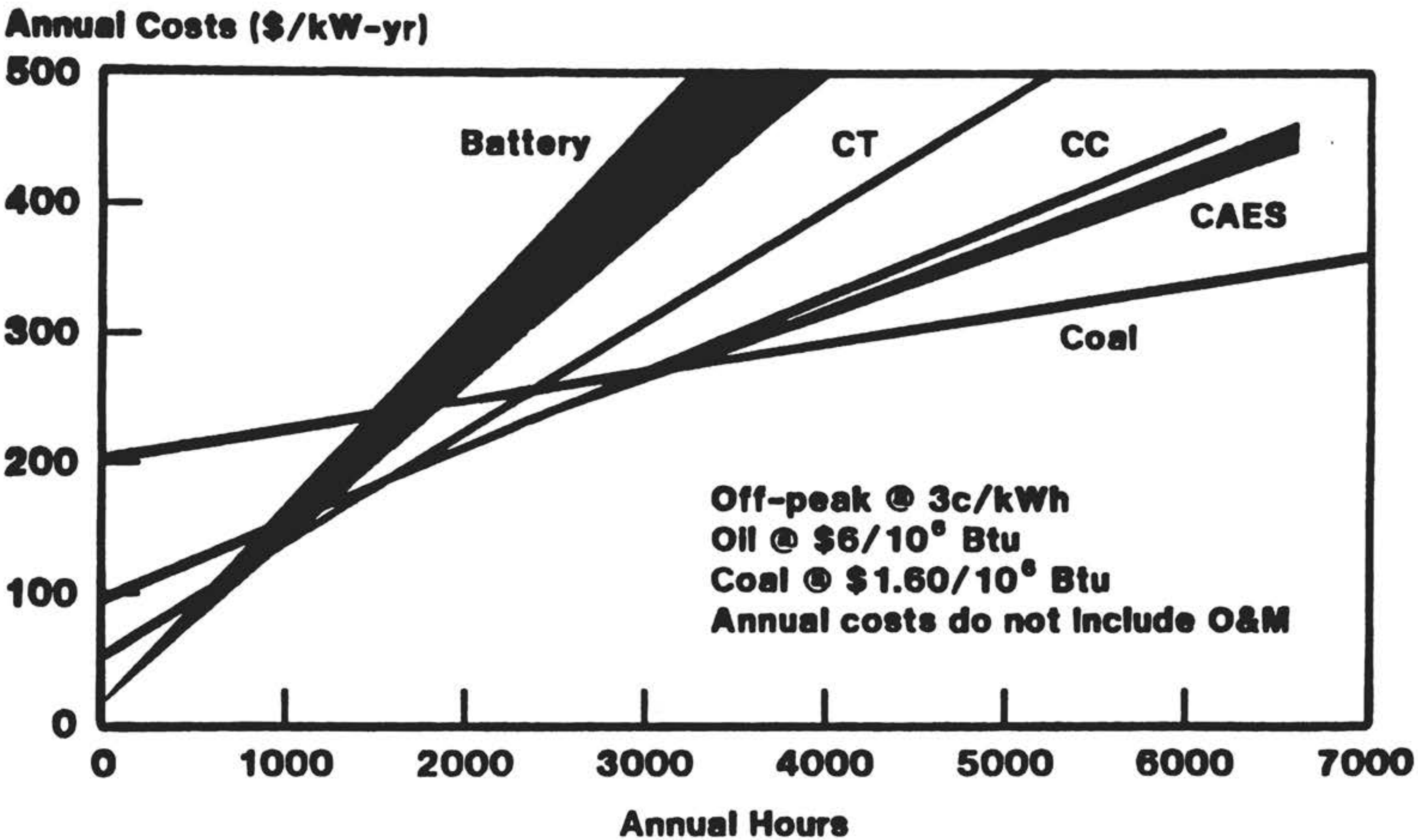


FIGURE 12 Screening curve.

achieve the lowest-cost system, the lower reservoir needs to be located 1000-1500 m below the surface reservoir. Since regulating pump-turbines capable of operating under such high heads were not commercially available a few years ago, EPRI funded the development of a high-head 2-stage pump-turbine. This development has reached the stage of a 1:6.5-scale model which is currently undergoing tests; results to date fully confirm the design and its capability to operate in the regulating mode under a 1500-m head.

EPRI staff and consultants are of the view that the technoeconomic basis for utility commitments to UPH projects now exists whenever a site-specific geotechnical evaluation has established the presence of suitable rock formations, and no further generic R&D appears to be required or is contemplated. While utility interest in UPH existed 5-10 years ago, it appears to have abated at present--almost certainly because of the large size, long construction time, and large financial commitments and risks associated with UPH projects of economic size (probably in excess of 1000 MW).

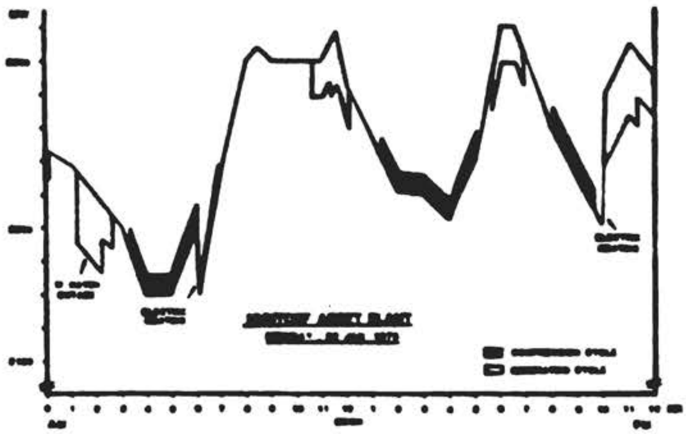
Compressed-Air Energy Storage (CAES)

Six years of reliable and efficient operation of the 290-MW CAES plant in Huntorf (Germany) have established CAES as an attractive new energy storage option for electric utilities. The Huntorf plant also has demonstrated the flexibility with which CAES can operate (see Figure 13), proving that the usefulness of a CAES plant extends well beyond simply shifting load from peak to off-peak periods.

In parallel with the commissioning and early operation of the Huntorf plant, EPRI and DOE undertook a series of studies with the objectives of extending the applicability of the CAES concept and further reducing its dependence on premium fuels. Most importantly, the results of several major design studies indicated that underground storage of compressed air was likely to be technically and economically feasible not only in caverns mined into salt formations (the Huntorf approach) but also in mined hard-rock caverns and in aquifers. As Figure 14 indicates, this could extend CAES siting to much of the continental United States.

Two significant uncertainties remained when this favorable conclusion was reached several years ago: (1) whether air dissolved in the pressure-compensating column can be kept from outgassing violently ("Champagne effect") during charging of hard-rock caverns with air, and (2) whether air can be recovered with adequate efficiency from aquifers in a daily cycle.* Modeling studies and several key experiments have largely resolved both concerns. For example, Figure 15 shows some of

*The feasibility of recovering, e.g., natural gas from aquifers at a slower rate is well established by the commercial practice of seasonal gas storage.



Huntorf Operation on January 22, 1979

FIGURE 13 Huntorf CAES plant scheduling.

What sites are suitable for CAES?

CAES requires a geological formation at a depth of 500-3000 ft that is virtually airtight and stable under modest daily temperature and pressure changes. Salt domes, hard-rock formations, or aquifers that can store compressed air occur throughout three-fourths of the United States. Such geologic media have been used for more than 40 years to store oil and natural gas; thus, site preparation and excavation technologies are well developed.

FIGURE 14

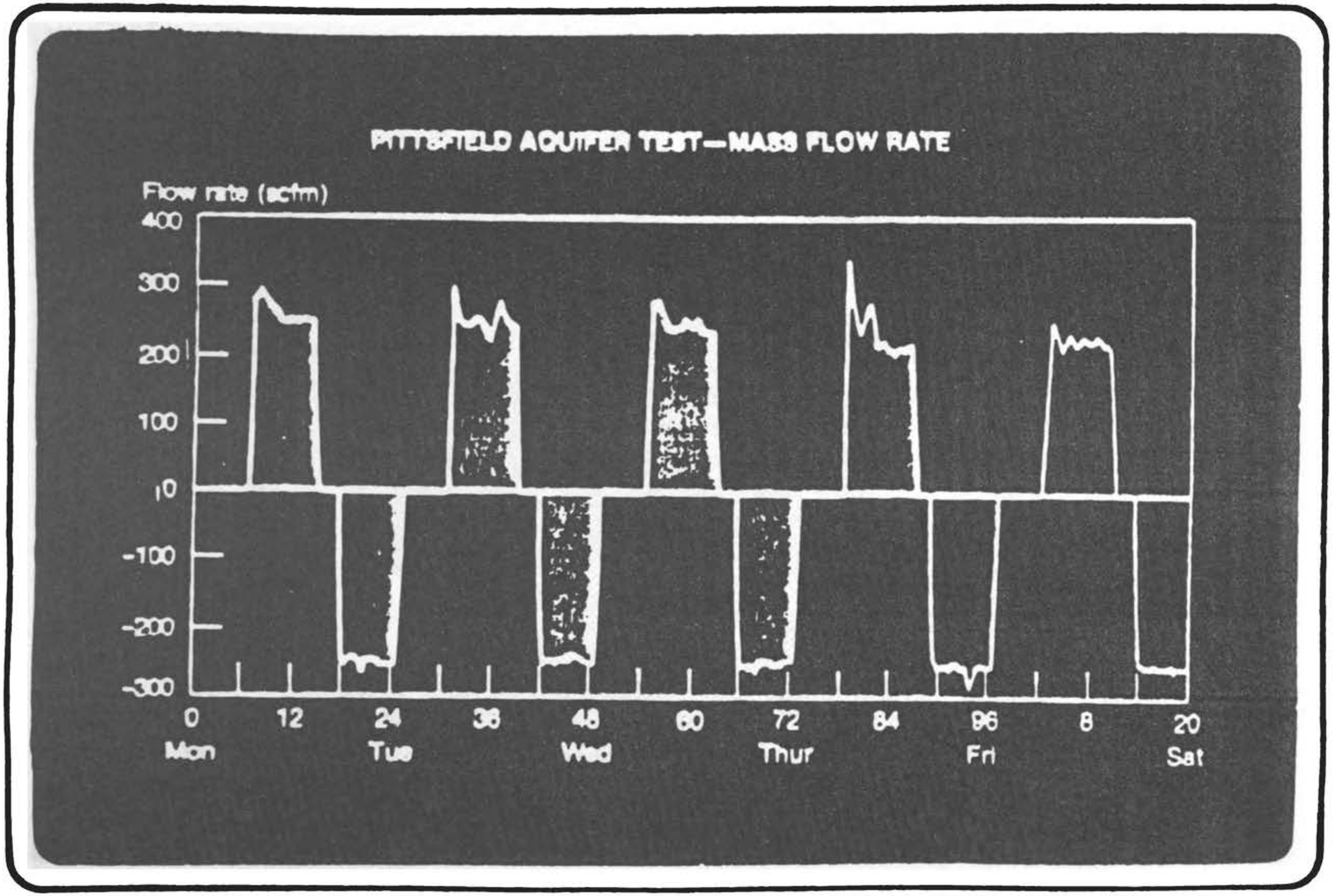


FIGURE 15 Pittsfield aquifer test--mass flow rate.

the results obtained in cyclic air pressurization experiments conducted with an aquifer near Pittsfield, Illinois. The data suggest that compressed air can indeed be recovered efficiently and at an adequate rate from a typical aquifer. This preliminary conclusion is not only of importance for the feasibility of siting CAES plants in many parts of the United States, but it points to the possibility of storing energy for more extended periods because the incremental cost of the capacity for storing air in aquifers could well be less than $1.00/kWh. If confirmed as technically and economically feasible, such extended storage would offer utilities interesting possibilities beyond daily and weekly load leveling, including system protection against extended outages of generating plants, ability to purchase and store seasonally available power, and, in the limit, leveling of seasonal loads. No other energy storage technique appears to have this potential.*

Over the last two years, studies at EPRI have led to the conclusion that the concept of CAES (especially systems using aquifers for storage) can very probably be extended economically to smaller sizes, e.g., 50 MW, or perhaps as little as 25 MW (see Figure 16). Inasmuch as these smaller CAES plants most likely can be constructed in less than three years, CAES should now be regarded as a modular storage/generation option capable of providing load-leveling and dynamic duties at highly competitive cost, in small sizes, with short lead times, and using only a fraction of the premium fuels required by gas turbine and combined cycle generating equipment. Ongoing work in EPRI's CAES program is addressing the possibilities for further reduction of premium fuel requirements--through use of suitable recuperators in the near term and by utilizing coal combustion or the stored heat from the compression half-cycle to reheat the expanding air during the generation half-cycle.

No U.S. utilities have as yet committed to CAES plants, but interest is building, and several economic evaluation efforts have been initiated. Where such evaluations have been completed, they tend to show large savings in fuel use and generating costs relative to oil or gas-fired peaking and cycling generation. Two commercial consortia comprising highly reputed turbomachinery vendors, A-Es and underground construction companies have formed to offer commercial CAES plants. EPRI expects to assist utilities willing to make CAES plan commitments by sharing some of the risks associated with first-of-a-kind plants. While CAES thus can be considered close to commercial, there is no

*The feasibility of seasonally storing warm or chilled water in aquifers has been investigated for a number of years, with inconclusive results. Air storage in aquifers promises to be technically much less difficult and thus more attractive.

PLANT SIZE	25 MW			50 MW			100 MW			220 MW		
GEOLOGY TYPE	AQUIFER	SALT	ROCK	AQUIFER	SALT	ROCK	AQUIFER	SALT	ROCK	AQUIFER	SALT	ROCK
PERFORMANCE DATA**												
HEAT RATE (BTU/KWH OUT)	3940	3940	3940	4000	4000	4000	4000	4000	4000	4090	3980	4015
ENERGY RATIO (KWH IN/KWH OUT)	.80	.80	.77	.80	.80	.79	.80	.80	.79	.70	.78	.74
LICENSING TIME (YR)	2	2	2	2	2	2	2	2	2	2	2	2
CONSTRUCTION TIME (YR)	2	2	2½	2	2	2½	2	2	2	3	3	4
COST*** (JANUARY 1984 $/KW)	614	664	1166	477	495	847	465	471	750	572	579	618
MARGINAL COST FOR ONE ADDITIONAL HOUR OF STORAGE	0.2	6	39	0.2	5	31	0.2	5	31	0.2	2	6

*DATA PRESENTED ARE FOR A 10-HR STORAGE SYSTEM (10 HR COMPRESSION, 10 HR GENERATION, 5 DAYS PER WEEK). DATA FOR OTHER HOURS OF STORAGE ARE AVAILABLE FROM EPRI (E.G., USING WEEKENDS FOR COMPRESSION). GENERALLY, THE COST FOR EXTRA STORAGE HOURS EQUAL THE VALUES GIVEN AS MARGINAL COST. THE 100-MW PLANT IS COMPOSED OF TWO 50-MW UNITS.

**THE PERFORMANCE DATA ARE TO BE INTERPRETED AS BTU OF FUEL NEEDED DURING GENERATION PLUS KWH OF ELECTRICITY NEEDED DURING COMPRESSION, WHICH TOGETHER GENERATE 1 KWH OF PLANT OUTPUT. THE HEAT RATE AT 20% PART LOAD HAS LESS THAN 7% DEGRADATION. THE ENERGY RATIO FOR THE 25- TO 100-MW PLANTS WILL LIKELY BE REDUCED BASED ON EPRI RESEARCH AND DEVELOPMENT NOW IN PLACE.

***COST INCLUDES TURBOMACHINERY, STRUCTURES, IMPROVEMENTS, MOTOR-GENERATOR, AIR STORAGE RESERVOIR, BALANCE OF PLANT, ENGINEERING DESIGN, CONSTRUCTION, MANAGEMENT, AND CONTINGENCY. INTEREST AND ESCALATION DURING THE CONSTRUCTION INTERVAL IS NOT INCLUDED.

FIGURE 16 Performance, licensing, construction, and cost data for CAES plants.

doubt that considerable additional R&D is required and justified to fully exploit the potential of CAES. Several recommendations appropriate for consideration in private sector and Federal programs are given in the final chapter.

Batteries

Secondary batteries have long attracted utility interest as being the potentially most flexible and widely usable method of load leveling, with the promise of characteristics such as rapid response, high reliability, good efficiency over the entire load range, and ready siting as well as quick installation of modular systems. Spurred by this promise and utility needs for more flexible alternatives to pumped hydro, major programs to develop load-leveling batteries have been underway in the United States for more than ten years.

The broad goals for these programs were and continue to be achievement of battery cycle life sufficient for utility applications (at least 2500 deep cycles, equivalent to 10 years of operation) with battery systems of sufficiently low cost (on the order of $100 or less per kWh of storage capacity). Ten years ago, the lead acid battery was the only, and, at best, marginal--candidate among the reasonably well-developed secondary batteries for achieving these goals. Most of the extensive R&D efforts since then have focussed on development of advanced electrochemical systems that offer reasonable promise of lower cost and longer life.

At this time, sodium-sulfur, zinc-chlorine, and zinc-bromine have emerged as the most promising electrochemical systems and, after years of development, as potentially practical and economically competitive batteries. The use of inexpensive negatives (sodium and zinc) and positives (sulfur, chlorine, and bromine) in these battery systems meets a necessary although not sufficient criterion for achieving low battery costs. All three systems have inherent promise also for long cycle life because of the basic simplicity of the electrochemical couples involved (absence of side reactions), and because their active materials are in the liquid state either at all times of operation (Na/S) or at least once each cycle when the battery is fully discharged (Zn/Cl_2 and Zn/Br_2). This feature is very advantageous since it prevents the cumulative buildup of deleterious changes in electrode structures.

Equally important, each of these three systems has additional, system-specific features that have allowed their promise for low cost and long life to be exploited in practical battery configurations. The sodium-sulfur battery features the use of beta alumina as both solid electrolyte and ideal separator, a unique advantage made possible by the fact that this ceramic material has excellent sodium ion conductivity at temperatures (around 300 to 350^{o}C) compatible with operation of sodium and sulfur electrodes as liquids of low vapor pressure.

For the zinc-chlorine and zinc-bromine batteries, the key features are (1) the storage of the normally very aggressive halogens as chemically bound but readily decomposed compounds (chlorine hydrate and organic bromine complexes, respectively, outside the electrochemical cells, and (2) battery operation with aqueous electrolytes at near-ambient temperatures and pressures, thus permitting use of inexpensive carbons and plastics as electrode support and electrolyte containment materials, respectively.

The reduction of these special features to engineering practice in cells and batteries has presented major technical and economic challenges for the development of sodium-sulfur and zinc-halogen batteries. The fact that none of these systems is as yet commercially available, despite more than a decade of intense R&D, attests to the difficulties of these challenges. Nevertheless, major progress has been achieved. Recent advances in the development of the zinc chloride system into a practical load-leveling battery have been significant. A 100-kW/500-kWh pre-prototype battery module has delivered over 100 charge/discharge cycles in the Battery Energy Storage Test (BEST) Facility during 1984. While this module still exhibited a number of imperfections that compromised reliability, none of these appear to be fundamental, and the extended test validated the basic design as well as the operability of this system. The next phase of development could involve fabrication and evaluation of a 2-MW/6-MWh prototype "Flexpower" battery during 1986. If design improvements to achieve acceptable reliability, efficiency, and production costs can be confirmed, early commercial Flexpower units could be deployed on utility systems later in this decade. This would represent the first large-scale application of an advanced battery and thus a major step toward making batteries for utility load leveling a reality.

Most important for the prospects of the sodium-sulfur battery, the properties of beta alumina as an electrolyte and its fabrication into electrolyte tubes are now sufficiently well understood for construction of single cells with a life of more than 2000 cycles and good prospects to eventually achieve 4000-5000 cycles. The last five years have also seen significant progress in most other areas of importance: sulfur electrode configuration, containers, seals, safety features, and manufacturing techniques. Not yet fully resolved are achievement of low-cost, reproducible starting materials and fabrication techniques for cells, upscaling of cells to larger sizes, and the low-cost assembly and reliable operation of groups of cells as batteries. These issues are being addressed in major programs funded by DOE and EPRI. If these closely coordinated programs are successful, a 500-kWh pre-prototype battery module could be available for evaluation in the BEST Facility beginning in 1988.

The zinc bromine battery has had a shorter and less intensive development history. Nevertheless, progress has been encouraging, and laboratory modules of 80-kWh capacity have demonstrated the feasibility of storing bromine as an organic complex and operating bipolar stacks of cells as batteries. Bromine management, electrochemical efficiency, and optimum design and materials for the bipolar cell stacks are the main issues being addressed in continuing development programs funded by DOE and EPRI in close coordination. Given a reasonable rate of technical progress, the goal of fabricating and evaluating (in BEST) a 500-kWh pre-prototype module by 1989 should be achievable.

Several other battery systems with interesting characteristics have been proposed and to some extent explored for the load-leveling application. Notably, these include several electrochemical variants of cells with zinc or iron negatives and redox couple positives, as well as an all-liquid flow cell based on an iron-positive and a chromium-negative redox couple. Although promising in some respects, these and other advanced systems do not appear to offer superior characteristics--in terms of lower costs, greater simplicity, and/or higher efficiency--compared to Na/S, Zn/Cl_2 or Zn/Br_2.

As noted earlier, ten years ago the lead-acid battery was not believed to promise a combination of sufficiently long cycle life and low cost that would qualify this rather mature technology for utility load-leveling applications. Since then, lead-acid technology has continued to improve and the price of lead has gone down. In a recent EPRI study, the technoeconomic potential of the lead-acid battery for leveling shorter-term load peaks of large electricity consumers was reexamined with the conclusion that in areas of high-cost peak power--as reflected by high demand charges--the use of lead-acid batteries on the customer's side of the meter could be financially beneficial to customers and utility. In response to significant utility interest, a 500-kW/500-kWh lead-acid battery system (including an appropriately sized inverter) is being evaluated in the BEST Facility for this short-duration, load-leveling duty cycle. Plans call for moving this prototype system to a utility customer site for a demonstration in 1985/86 of this new utility load management option.

Superconducting Magnetic Energy Storage (SMES)

The concept of storing energy in the superconducting coils of electromagnets has been under study for more than ten years in several U.S. laboratories. The attractiveness of the SMES concept for utility applications lies in its potentially very high efficiencies (on the order of 90 percent compared to the 65 to 80 percent range typical of most other storage techniques) and rapid electric response, both a consequence of storing energy directly as electricity.

Also as a direct consequence, the power-related portion of SMES capital costs is low (see Figure 11) since it involves only AC/DC conversion equipment, as with batteries. On the other hand, all studies to date point to relatively high capital costs per unit of storage compared to other technologies and, also, to a strong scale factor in these costs. A recent analysis of SMES designs and costs indicated a total capital cost of around $1350/kW for a 1000-MW/5000-MWh system based on state-of-the-art designs and materials. Over half of this cost is related to the superconductor coil material and its fabrication and support structure. The study also suggested that costs might be reduced to as low as $900/kW with a lower-cost superconductor and improvements in system design. At this cost, SMES would be competitive with other storage methods. The recent development of an improved niobium-titanium superconductor with a 2 times higher critical current density than the niobium-titanium material assumed in the recent design studies lends support to the belief that SMES costs can eventually be reduced, perhaps significantly.

One important question continues to face SMES and must be resolved before more extensive development can be justified: which (if any) beneficial roles can SMES play in future power systems? With present prospects for electrical and cost characteristics, SMES applications appear to be restricted to large installations that could be used to level shorter-term load peaks and provide spinning reserve for larger interconnected power systems. More readily realized and broader applications would seem open to SMES only if its capital costs could be reduced to the point where systems well below 1000 MW would become economically competitive. More research on critical aspects of SMES is needed before the prospects for achieving lower costs can be assessed with reasonable confidence.

NEEDS IN THE DEVELOPMENT OF LOAD-LEVELING TECHNOLOGIES

The considerations presented in this paper indicate that the importance of electric load leveling is likely to grow: load factors are not improving while the costs of underutilized base load capacity and of meeting peak loads are increasing. Timely deployment of economic load-leveling systems promises to reduce electricity costs, improve the ability of utilities to meet their loads, and reduce the country's dependence on premium fuels.

The analysis also suggests that a combination of strategies and techniques on both sides of the meter will be the most effective approach to leveling the loads on U.S. power system generation (and transmission) capacity. Supply-side energy storage techniques are capable of leveling daily and weekly cycles year-round, can provide important dynamic benefits for power systems, and can be operated under complete control of a utility. Demand-side energy management/ load-leveling strategies can help level seasonal load variations and contribute to daily load leveling, especially during peak seasons. They can represent the lowest-cost strategy for customers as well as for utilities, and they will help defer the need for utility investments in peaking capacity. On the other hand, penetration of some of the most attractive options (such as commercial cool storage) is likely to be relatively slow, and utilities will have only limited control over implementation and operation of DSM options on their systems.

Presently commercial technology options fall short--in terms of their applicability, versatility, and performance--of meeting the needs for broadly usable and cost-effective supply-side and demand-side load-leveling/energy management techniques. A number of potentially attractive candidates have been identified, and extensive development has been under way especially for supply-side energy storage techniques. The Federal Government and EPRI have been continuing to provide significant funding for these developments through a sequence of R&D programs.

More than ten years of development have resulted in highly significant progress and good prospects for eventual commercial success for several key technologies. However, significant barriers remain to be overcome before success is assured. In part, these barriers are still technical. As technologies are moving closer toward commercial readiness, however, the perceptions of significant technical and financial risks on the part of potential vendors and users are becoming major barriers to commercialization. These barriers tend to be especially high if the technologies represent entirely new ways of meeting key functional requirements, and if the implementing organizations behave conservatively because of the nature of their businesses. Both of these factors apply to load leveling through energy storage on electric utility systems.

This situation, and the private sector's as well as the Government's interest to achieve fruition of their significant investments to date in the development of load-leveling technologies, argue for continued, strong programs for development and evaluation of supply-side and demand-side load-leveling technologies and systems. Specific recommendations for critical roles and appropriate activities are summarized below for key technologies. It is recognized that these recommendations are not entirely derived from the discussions in this paper. They are offered on the basis of EPRI's and the author's own analyses, in the interest of providing a broad R&D perspective for consideration by DOE.

SUPPLY-SIDE ENERGY STORAGE TECHNOLOGIES

Compressed-Air Energy Storage

Goal: Expand potential applications for CAES and further reduce oil/gas use

Role: Participate on a significant level in R&D of advanced CAES concepts

Activities: Conceptualization, analysis, and experimental validation of CAES schemes involving thermal storage, advanced coal-firing techniques, etc.; theoretical and experimental investigations of longer-term air storage in aquifers

Goal: Enhance prospects for early applications for CAES

Role: Share risk and cost of early demonstrations

Activities: Development and application of geotechnical evaluation methods (especially for aquifer-based air storage)

Batteries and Chemical Energy Storage Systems

Goal: Ensure successful development of sodium-sulfur, zinc-chloride, and zinc-bromide load-leveling batteries

Role: Continue major DOE role in ongoing, coordinated national programs of battery development and evaluation

Activities: Battery technology development; technology validation in BEST Facility; technology improvement programs in support of private-sector R&D efforts

Goal: Explore the potential of alternate electrochemical and chemical systems for load-leveling/energy storage

Role: Take lead in exploratory R&D in above areas

Activities: Conceptualization, critical analysis, and selective experimental investigation of advanced battery and chemical systems with potential for efficient, economic, and flexible energy storage

Superconducting Magnetic Energy Storage

Goals: Explore and advance technoeconomic prospects of SMES; expand potential applications

Role: Continue to participate in coordinated national R&D program on SMES

Activities: Exploration and development of lower-cost superconducting materials; conceptualization and critical analysis of advanced designs; small-scale validation of beneficial applications through power systems analyses

Load-Leveling/Power Systems Analysis

Goal: Identify optimum applications and economic benefits of energy storage on power systems

Role: Participate in and enhance current private-sector research in above area

Activities: Refinement and/or development of applicable models and analyses, taking into account detailed (including dynamic) characteristics of generation, storage, and power systems

DEMAND-SIDE ENERGY MANAGEMENT TECHNOLOGIES

Cool Storage

Goal: Expand applicability of load-leveling cool storage in commercial and residential buildings

Roles: Support private-sector efforts on nearer-term technologies and carry lead in R&D on advanced systems

Activities: Requirements analysis; exploratory development emphasizing systems utilizing latent heat; validation of successful developments on appropriate scale

Load Control and Management Systems

Goal: Expand applicability, increase flexibility, and reduce cost of systems for load control/management

Roles: Continue and increase participation in private-sector R&D and demonstration programs

Activities: Requirements and systems analyses; development and testing of local and dispersed logic control concepts/systems; validation of hardware and systems performance; conduct an analysis of larger-scale experiments (example, Athens)

Integration of Supply-Side and Demand-Side Energy Management Strategies and Systems

Goal: Develop methods for and identify benefits of integrated planning and operation of supply-side and demand-side management technologies

Roles: Participate in and enhance private-sector research in this area

Activities: Development of integrated supply/demand load-leveling/management models; validation of models on appropriate scale and/or for advanced supply-side and demand-side management technologies.

ELECTRICAL COMPONENTS

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INTRODUCTION

Because the electrical components presentation is merely one of several segments in a workshop on electric energy systems research, the author has made a conscious effort to refrain from addressing those electrical components that will most likely be covered in other segments. For this reason there is no discussion of dc components, nor of anything specific dealing with overhead or underground transmission line components. There is, however, a short section dealing with transmission, from a systems standpoint.

An electrical system is composed of a great many components, but only the most significant are addressed here because of presentation time constraints. Considering the objectives and breadth of the workshop, this approach appears to be reasonable and should not lead to any undue complication.

The components to be addressed are power transformers, circuit breakers, reactors, capacitors, and control systems, followed by a general treatise on transmission systems.

For each selected component an outline-type presentation follows, generally addressing scope (i.e., numbers, sizes, etc., where possible), future prospects, and results/needs.

POWER TRANSFORMERS

Scope

-- As of the end of 1983 there were about 26,000 power transformers (115kV and above) in use in the United States with a total capacity of $\pm$2300 GVA

-- By 1990 there will be about 30,000 such transformers with a total capacity of $\pm$2900 GVA

-- An increase of 15 percent over a seven-year period

Types and High Side Voltage Levels

Of those installed in the last 10 years:

- Generator stepups--9 percent of total number--mostly at 115kV-345kV level; some at 500kV, a few at 765kV
- Auto transformers--40 percent of total--linear breakdown between voltage level with highest number at 115-161kV level decreasing to 765kV level
- All other types of transformers--51 percent of total--by far most of these were in the 115-161kV class

Average Bank Size

Obviously as the voltage level goes up, so does the bank size

Voltage Level	Gen. Step-Up	Autos	Other
115-161kV	190MVA	65MVA	35MVA
230kV	350	200	50
345kV	700	400	100
500kV	950	800	1300
765kV	1800	1200	--

Future Prospects

- Don't look for significant change in transformer MVA capacity ratings
- Expect even closer designs by manufacturers--tailored toward planned use of specific units
- Lower loss units will be economically justified
- Longer planned life of units (both existing and new) by users
- Increasing environmental concerns--noise, fluid leaks

Results/Needs

- Need to know operating conditions to which transformer is exposed, over time, and impacts thereof (both new and existing units)
- Want to know when a transformer is approaching failure

-- Potential for short term cyclic, higher load carrying ability

-- Joint manufacturer/user/EPRI meeting of minds to address future transformer requirements in the broad sense might be in order

-- Reduce relatively low PCB levels (less than 50ppm) to zero ppm PCB in existing transformers

-- Nonflammable, nontoxic dielectric cooling medium

CIRCUIT BREAKERS

Scope

-- As of the end of 1983 there were almost 40,000 circuit breakers (115kV through 765kV) in service in the United States.

-- By 1990 this number is expected to approach 45,000

-- An increase of 13 percent over a seven-year period

-- About 1,500 distribution class circuit breakers were installed in 1983

Voltage Levels

-- Of those breakers (115kV through 765kV) included above:

72 percent are in the 115-161kV class
18 percent are in the 230kV class
7 percent are in the 345kV class
3 percent are in the 500 and 765kV class

-- By the year 1990, the percentage in the 115-161kV class will decrease slightly with the offsetting increase appearing in the 345kV and above classes

Future Prospects

-- Required interrupting capacities will probably still increase somewhat as more transmission is installed

-- There will be an increased use of SF_6 gas bus/breaker stations as compact designs become necessary in space scarce locations

Results/Needs

-- Higher interrupting capacity breakers will be required unless system designs can offset tighter operating systems

-- Faster breakers

-- Expanded use of SF_6 generates following needs:

- techniques to locate and analyze faults
- ability to determine change in dielectric over time
- how to "handle" arc byproducts

REACTORS

Scope

-- As of the end of 1983 there were about 46,000 shunt reactors (115-765kV) in service in the United States.

-- By 1990 this number is expected to be about 61,000

-- An increase of about one-third over a seven-year period

Voltage Levels

-- Of those reactors included above:

10 percent are in the 115-161kV class
6 percent are in the 230kV class
24 percent are in the 345kV class
43 percent are in the 500kV class
17 percent are in the 765kV class

-- No significant change in the distribution is expected in the year 1990

Future Prospects

-- As shown above, significant increase in number of units forecasted as EHV transmission systems grow

-- More systems analysis integrating transmission line characteristics, line loadings, switching conditions, other system components

Needs

-- Reduce losses

CAPACITORS

Scope

-- As of the end of 1983 there were about 24,000 series and 37,000 shunt capacitors in service in the United States on 115kV through 500kV systems

-- By 1990 these numbers are expected to be approximately 29,000 series units and 50,000 shunt

-- These increases are 21 percent (series) and 35 percent (shunt) over the seven-year period

Voltage Levels

-- About 75 percent of the series capacitors exist on 500kV systems, 20 percent on 345kV, and small amounts on the 115-230kV. This distribution is not expected to change by 1990.

-- About 60 percent of the shunt capacitors exist on 115-161kV systems, 25 percent on 230kV, 10 percent on 345kV, and 5 percent on 500kV. Again, this distribution is not expected to change by 1990.

Future Prospects

-- As shown above, significant increase in number of units forecasted as loads are pushed over longer distances and system contingency conditions are evaluated

-- Influenced by Static Var Control equipment

Needs

-- Reduced space requirements

-- Larger capacity units

-- Liquid-free units

TRANSMISSION SYSTEMS

Concerns

-- Difficult, costly, long time frames to license and build new ones

-- Generation getting more remote from load

-- Push to transfer more power between regions

-- Existing lines not getting any younger, but their importance will increase

Results

-- Push more power over same corridor

-- Overload some portions of network before others

-- Underground network segments in loading jeopardy

-- Less reliable systems and increased maintenance

Needs

-- Higher capacity lines on existing corridors

-- Real time data and knowledge of how to use it

-- Control power flows in network segments

-- Improved, effective replacement methods incorporating programmed upgrading

CONTROL SYSTEMS, ETC.

A whole new look at substation control systems--including protective relaying, metering, status/data retention and transfer, and communication systems--needs to be taken. By integrating such current technologies as microprocessors, minicomputers and fiber optics, a better system must be developed that does not sacrifice system/equipment security and reliability.

Smart protection, control, and communication systems might permit:

- Improved coordination and equipment/system protection through inclusion of more parameters (both local and remote) under various operating conditions
- Retention of more information for later analysis (either system disturbances or equipment loading history)
- Selection of what information needs to be immediately transferred to a control center
- Easier change of protection settings based on various operating conditions
- Automatic "talking" between substations
- Shorter substation construction schedules
- New opportunities for load management

GROUP 2

RELIABILITY

EMP EFFECTS ON ELECTRICAL POWER SYSTEMS

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- EMP PHENOMENOLOGY & ENVIRONMENTS APPLICABLE TO POWER SYSTEMS
- DESCRIPTION OF POWER SYSTEMS
- POTENTIAL EMP EFFECTS ON POWER SYSTEMS
- SUMMARY

FIGURE 1 Outline.

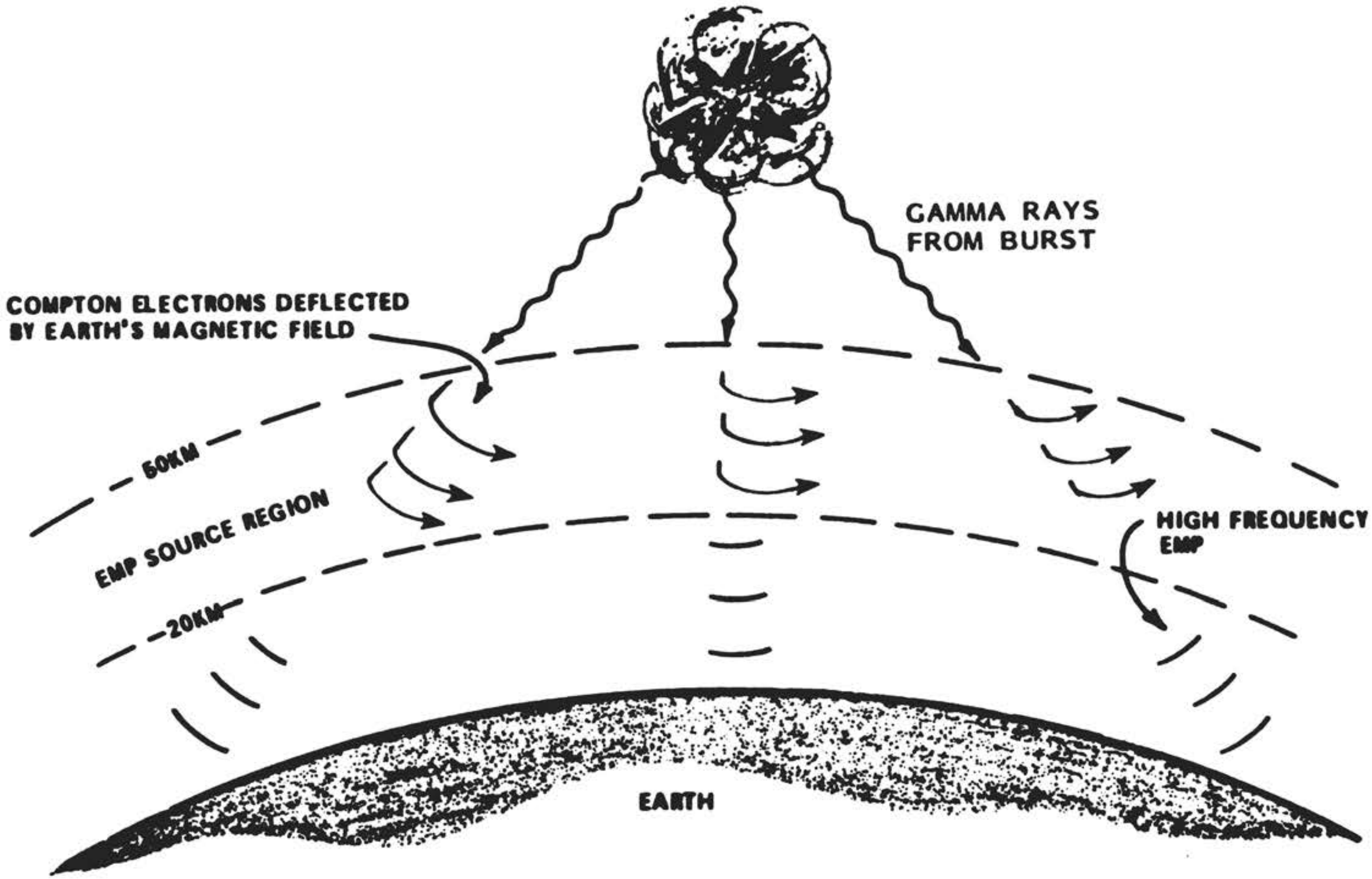

FIGURE 2 High altitude EMP generation model.

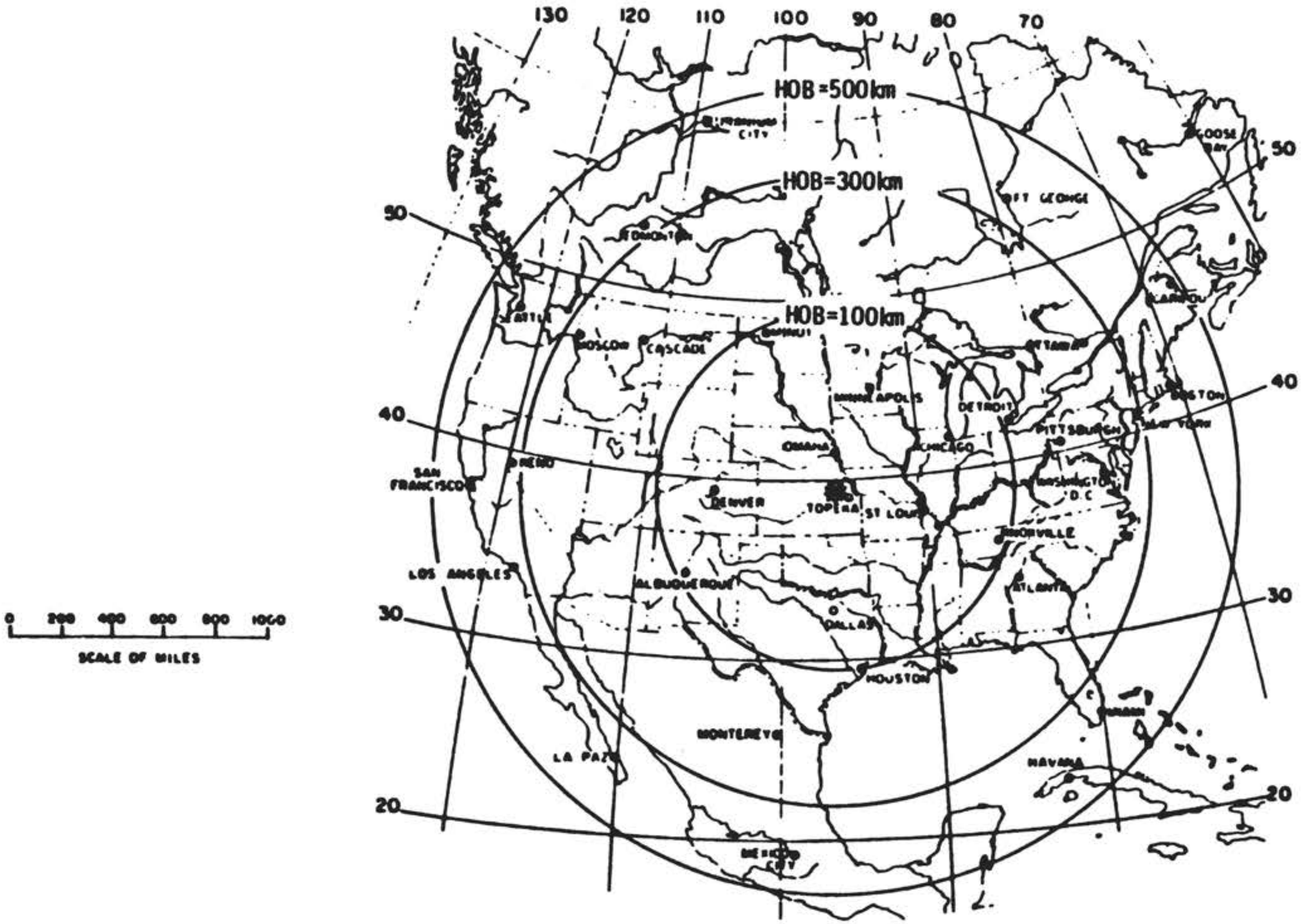

FIGURE 3 Areas of coverage of high altitude EMP.

	TYPE	AFFECTING	TYPICAL STRESSES	EFFECTS
(1)	HIGH FREQUENCY EMP	• COMM CENTERS • ANTENNAS, COMPUTERS	~ 1000's AMPS	CIRCUIT UPSET/ BURNOUT
(2)	MEDIUM FREQUENCY EMP	LINES CONNECTING NODES	~ 1000 AMPS	CIRCUIT UPSET/ BURNOUT
(3)	MHD EMP	LONG LINES	1 KV FOR 100 KM LINE	PROTECTIVE SHUTDOWN

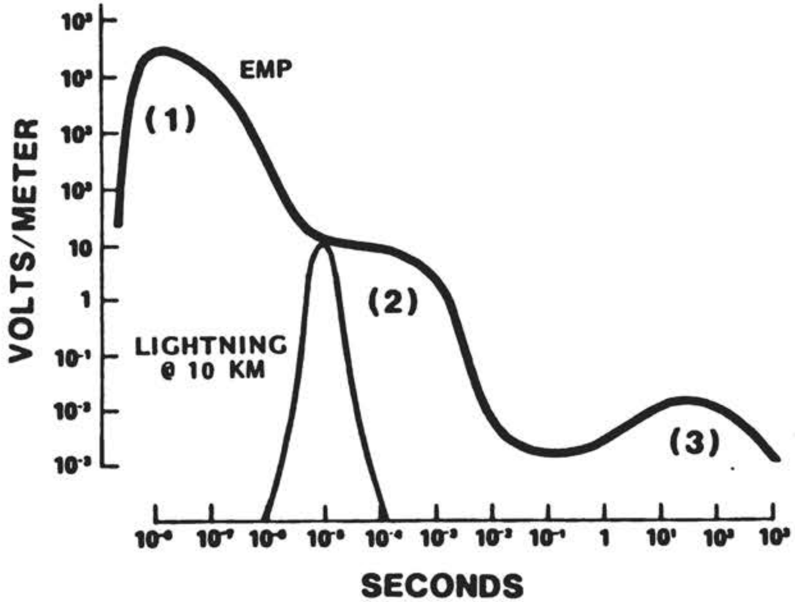

FIGURE 4 High altitude EMP characteristics.

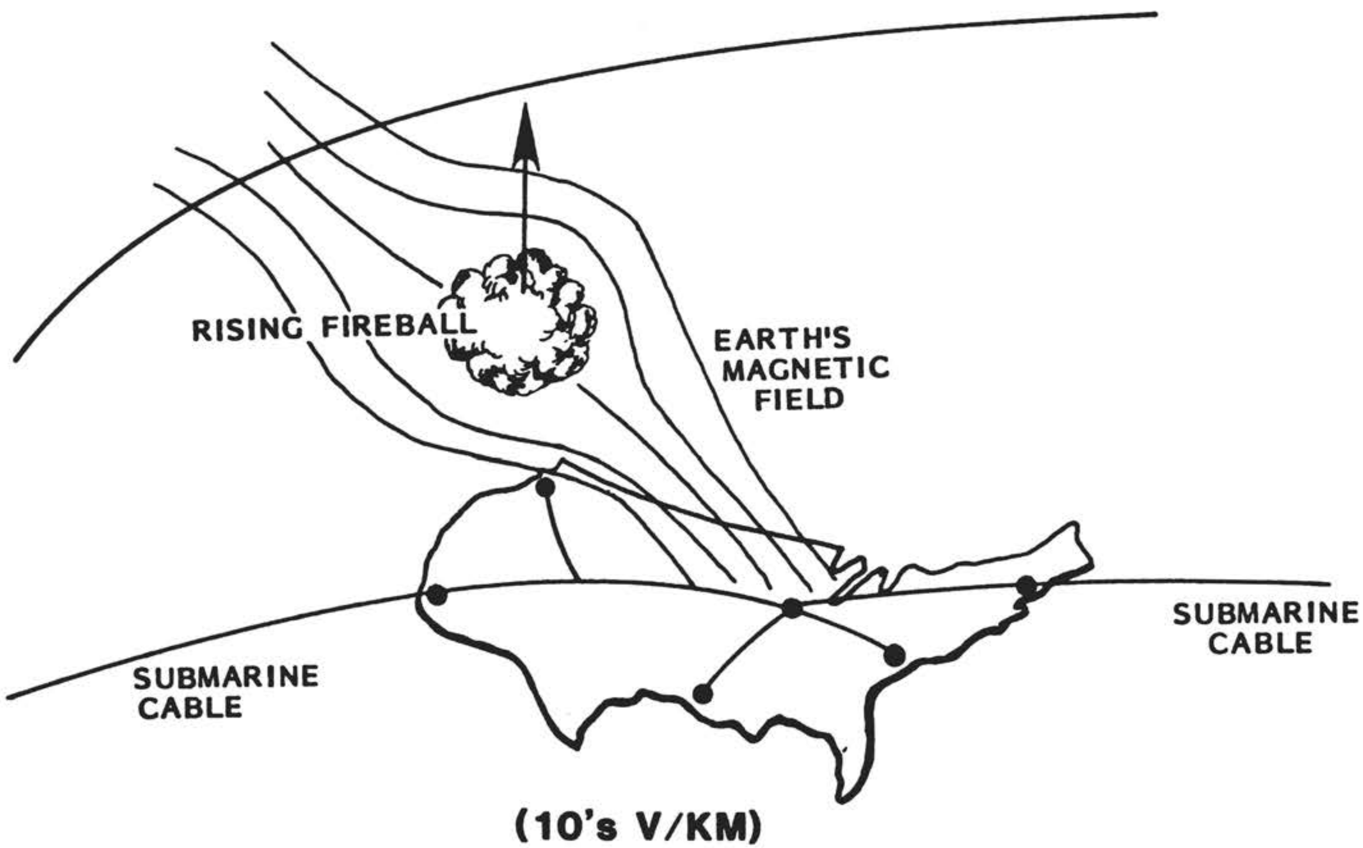

FIGURE 5 High altitude MHD EMP phenomenology.

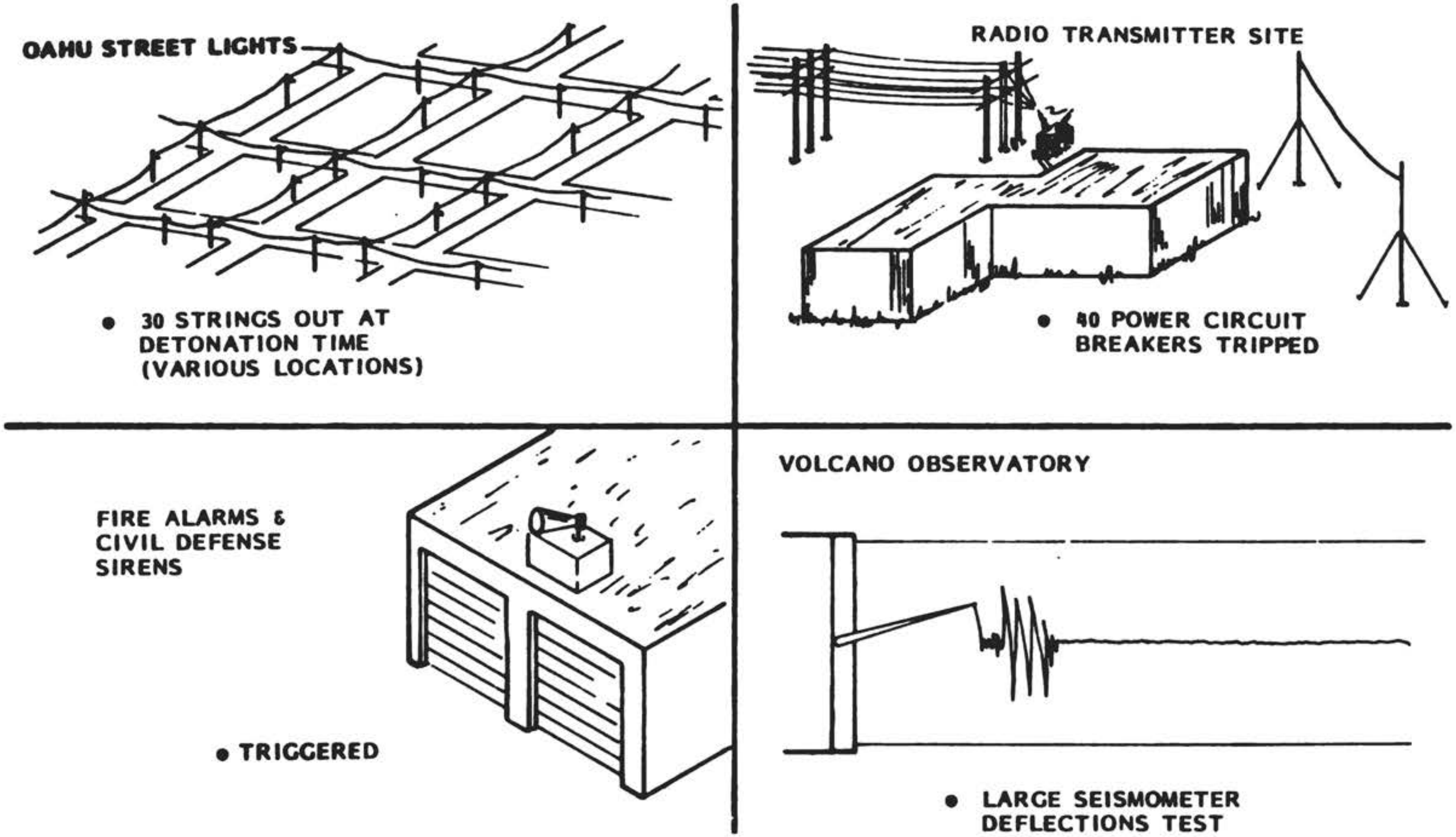

FIGURE 6 High altitude nuclear test effects in Hawaii (2000km away).

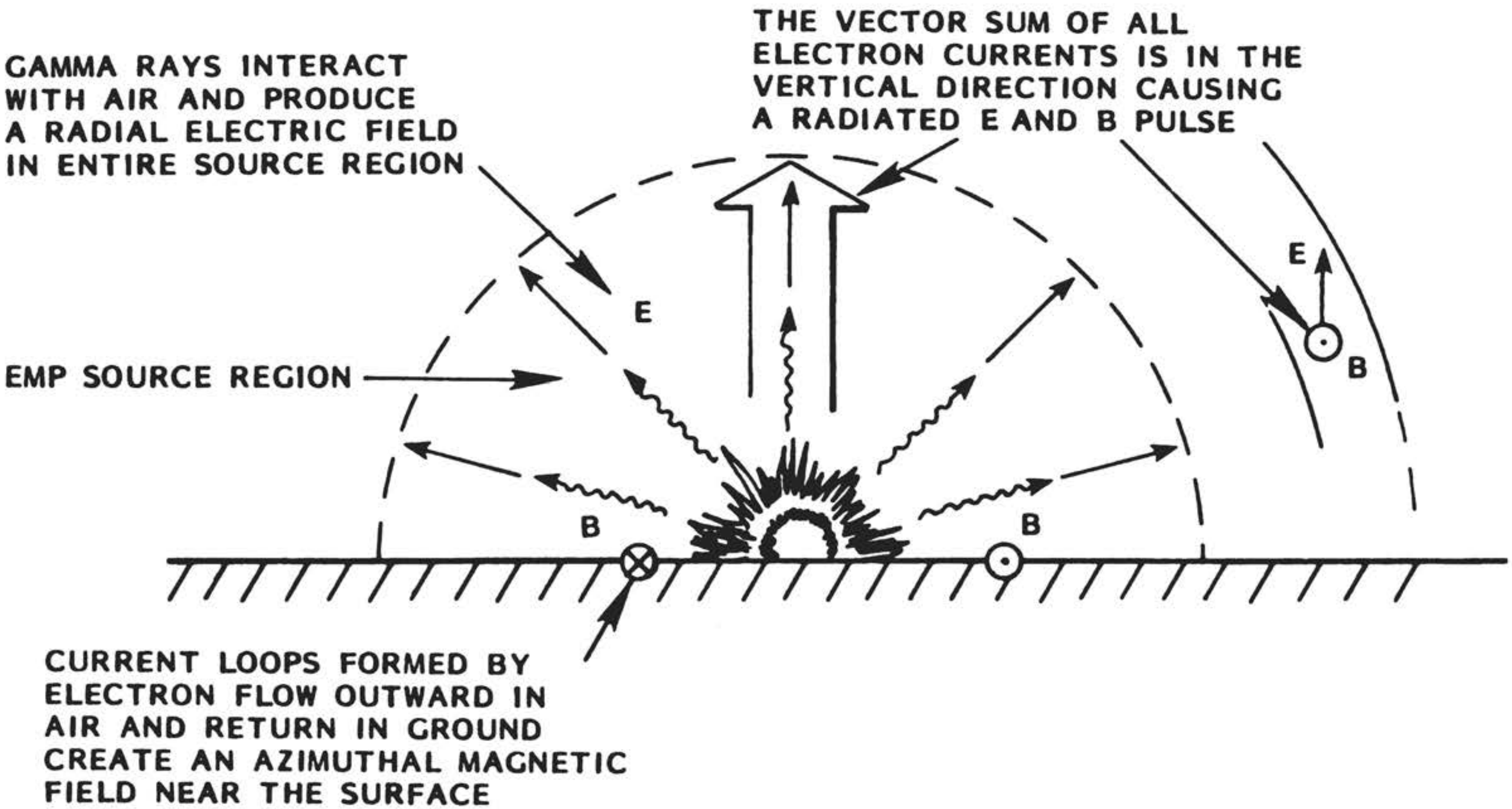

FIGURE 7 Surface burst EMP generation model.

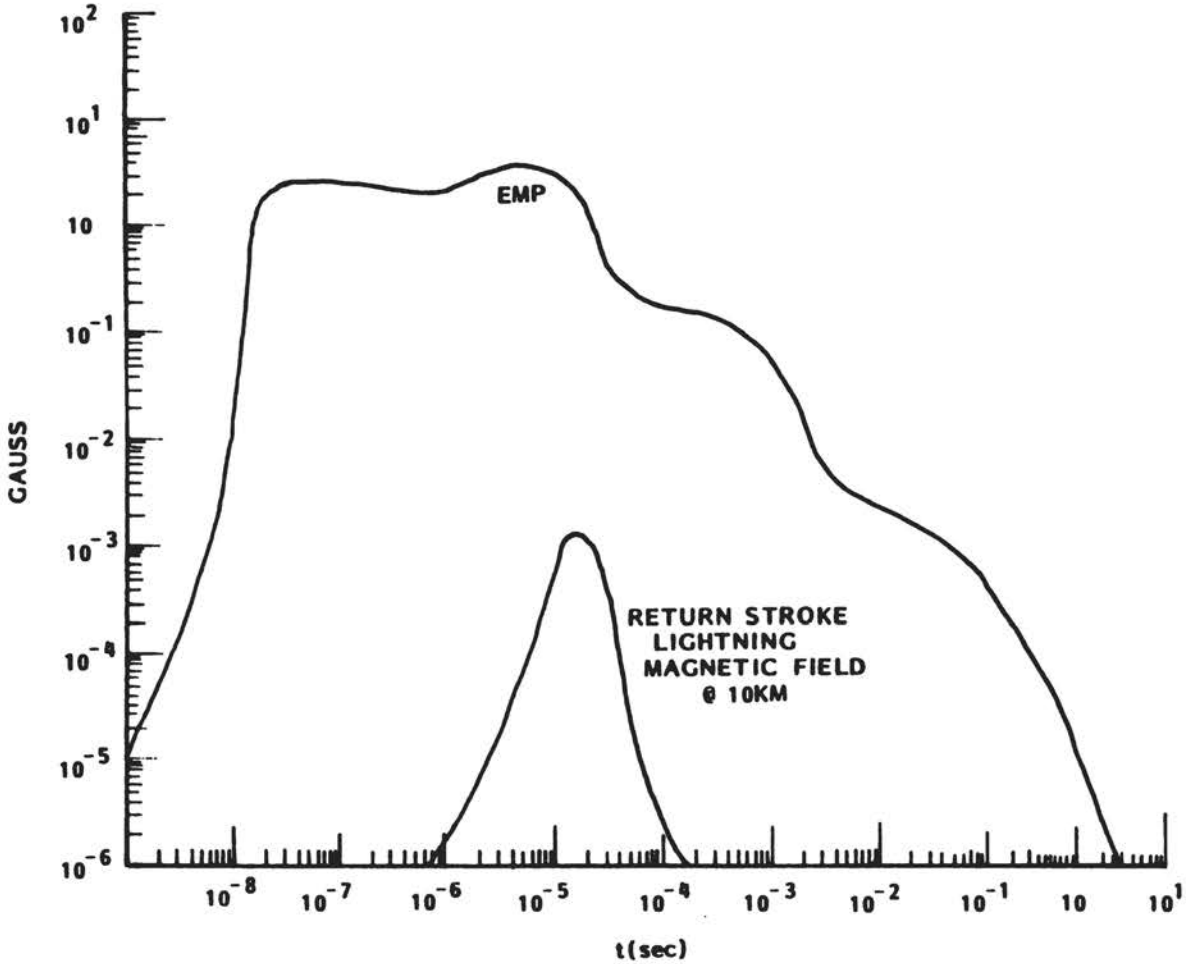

FIGURE 8 Ground burst EMP magnetic flux.

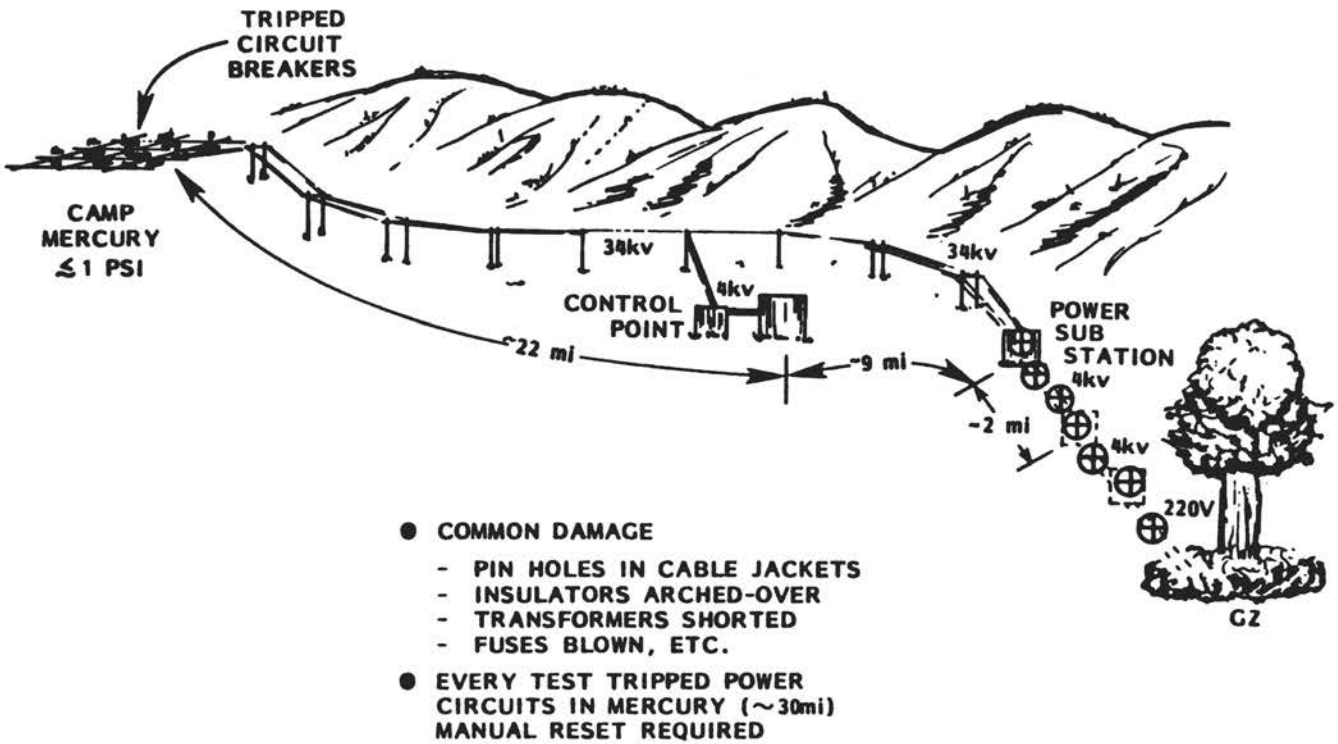

FIGURE 9 Power system damage.

- LARGE "ANTENNAS" COUPLE TO HEMP MOST STRONGLY: POWER LINES

- CHARACTERISTIC EMP COUPLING

EMP pickup "Antenna"	Open Circuit Voltage	Short Circuit Current	Pulse Rate of Rise	Coupled Energy
• POWER LINES - ABOVE GROUND	10^6 Volts	$3x10^3$ Amps	10^{12} V/Sec	10^3 Joules
• ABOVE-GROUND COMM LINES	10^6 Volts	$3x10^3$ Amps	10^{12} V/Sec	10^3 Joules
• LARGE STRUCTURES	$2x10^5$ Volts	$4x10^3$ Amps	10^{11} V/Sec	10^2 Joules
• BURIED POWER LINES	$3x10^3$ Volts	10^2 Amps	10^9 V/Sec	10 Joules

FIGURE 10 Typical EMP interaction with power systems.

VERY LARGE TRANSIENTS (~1000V) AT ELECTRONIC EQUIPMENT INTERFACE WILL PROBABLY CAUSE DAMAGE

- INDEPENDENT OF ELECTRONICS TECHNOLOGY

WHETHER SMALLER TRANSIENTS (~100V) CAUSE DAMAGE DEPENDS ON DETAILS OF INTERFACE

- SERIES RESISTANCE FOR SEMICONDUCTOR JUNCTIONS
- NARROW BAND FILTERS FOR RADIO RECEIVERS

WHETHER SMALL TRANSIENTS (~10V) CAUSE SIGNIFICANT LOGIC UPSET DEPENDS ON HARDWARE AND SOFTWARE DETAILS

- ERROR RECOGNITION AND CORRECTION

FIGURE 11 General observations on vulnerability of electric systems.

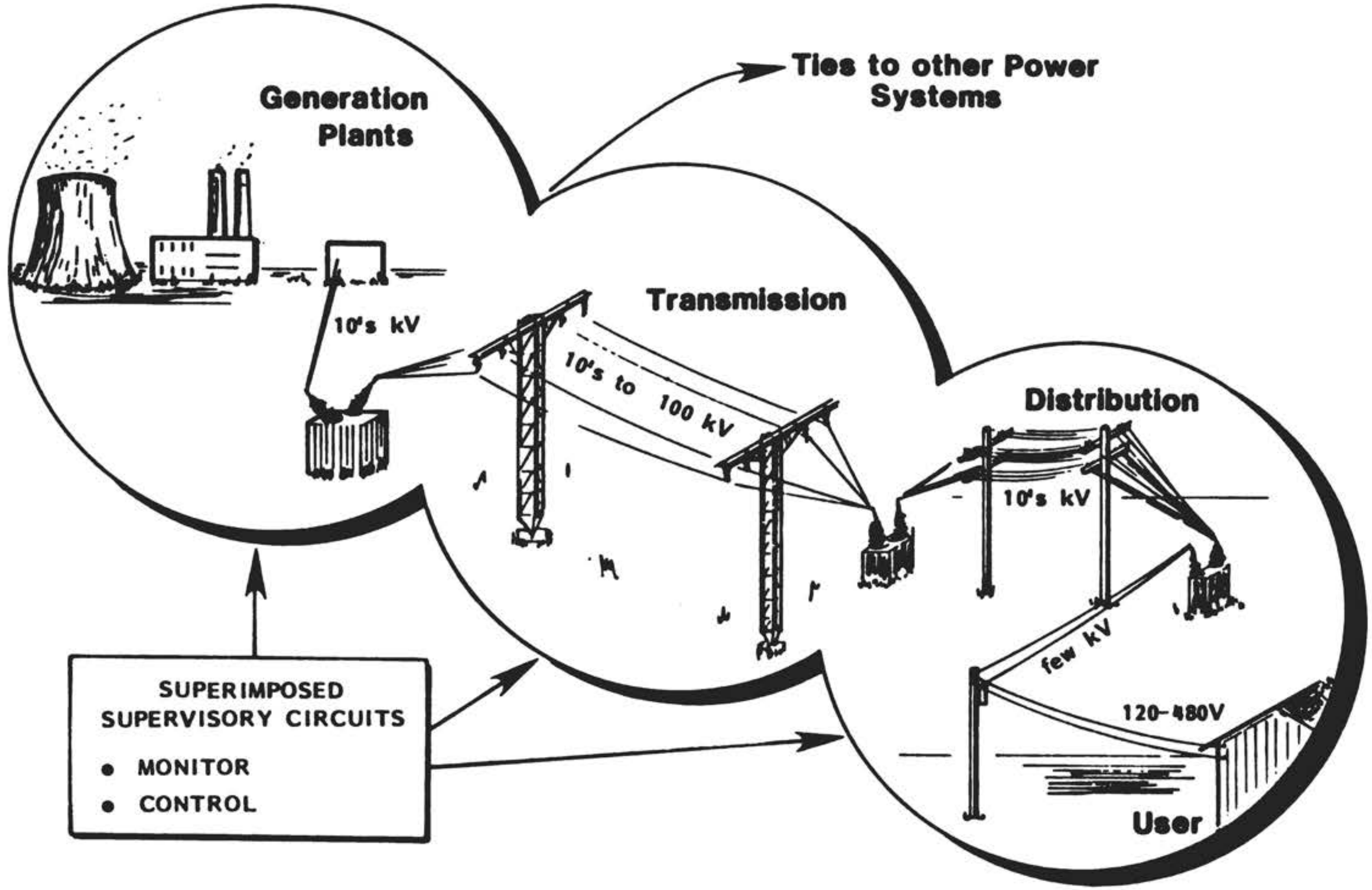

FIGURE 12 U.S. electrical power systems.

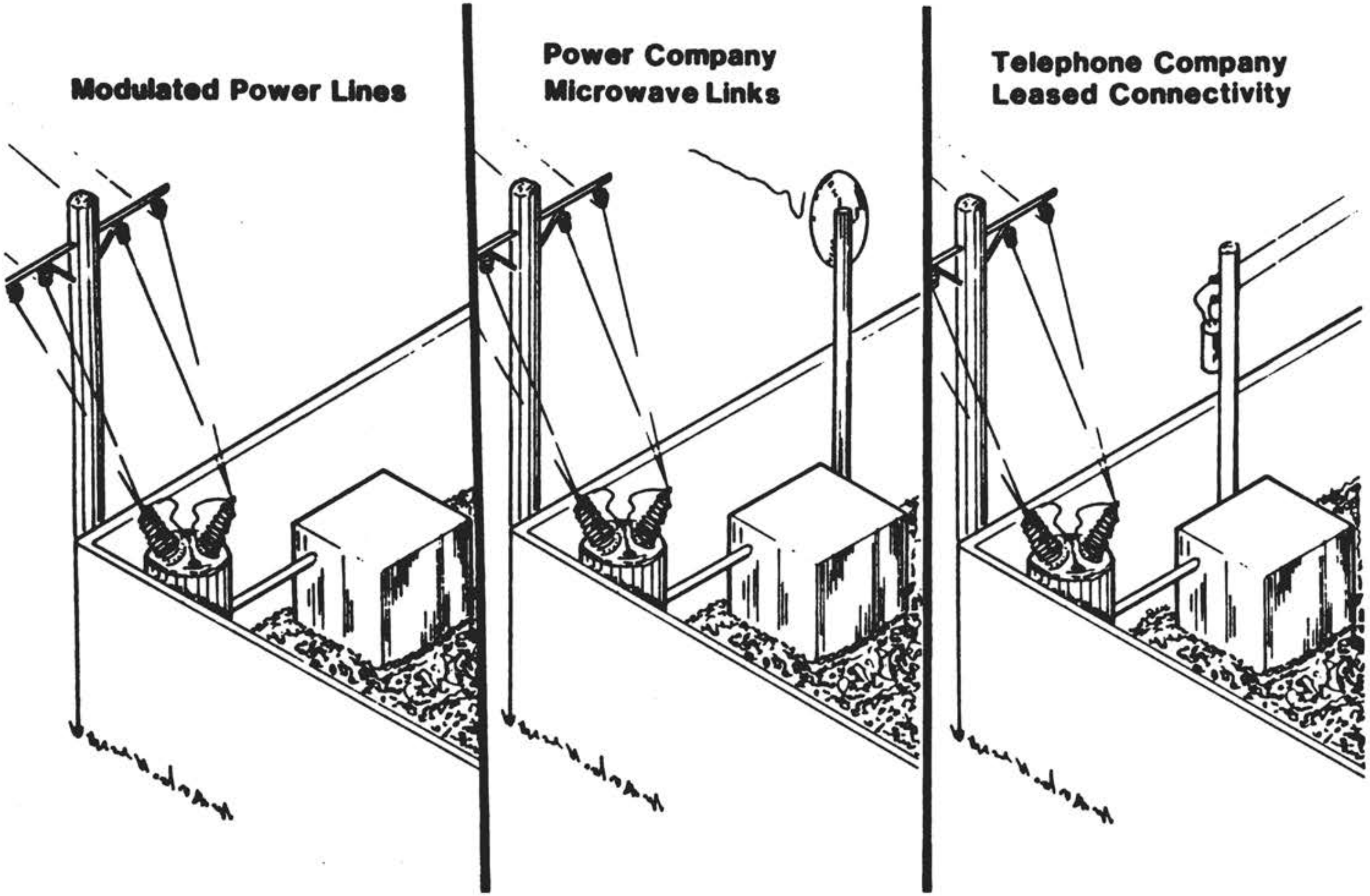

FIGURE 13 Supervisory circuit types.

	EMP	Lightning
ENERGY & TIME HISTORY	• FASTER RISETIME • HIGHER PEAK	• GREATER TOTAL ENERGY • SLOWER PULSE
SPATIAL EXTENT	• SIMULTANEOUS OVER TOTAL GRID	• VERY LOCALIZED
INJECTION	• CONTINUOUS ALONG LINE • CHARGE & VOLTAGE BUILD AT TERMINALS	• POINT SOURCE ON LINE • PULSE MOVES AWAY FROM POINT
SURGE ARRESTOR ACTION	• DOES NOT ACT IN TIME TO DIVERT MOST OF PULSE	• SHORTS PULSE TO GROUND

FIGURE 14 EMP versus lightning effects on power systems.

- NUCLEAR POWER PLANTS - 1982 ANALYSIS & LIMITED TESTING
  - EMP SUSCEPTIBLE MONITOR & CONTROL SYSTEMS
  - MOST PROBABLE EMP RESULTS: SHUTDOWN
    - UNNECESSARY ACTIVATION OF SAFETY SYSTEMS
    - SIMILAR TO SEVERAL LIGHTNING CAUSED SHUTDOWNS

- CONVENTIONAL POWER PLANTS
  - EMP SUSCEPTIBLE MONITOR & CONTROL SYSTEMS
  - MOST PROBABLE EMP RESULT: TRIP OUT (DISCONNECTION)
    - MONITOR/CONTROL SYSTEM FAULT
    - POWER SYSTEM FAULT CREATED OVER-UNDER-SPEED THEN SAFETY TRIP OUT

FIGURE 15 EMP effects on generation systems.

- POWER LINES & SUBSTATIONS*
  - CORONA & FLASHOVER AT INSULATORS
  - DISCHARGE THRU ARRESTORS
  - DAMAGE TO INSULATORS (PUNCTURE, ETC)
  - BURNOUT FUSES & RELAYS
- POWER RECLOSURES (CIRCUIT BREAKERS)*
  - OPEN AUTOMATIC RECLOSURES
  - RECLOSURES CYCLE 2 - 3 TIMES, THEN:
    - DAMAGE/SHORTED LINE LOCKS RECLOSURE OPEN
    - MULTIPLE EMP PULSES LOCK OPEN EVEN IF NO PERMANENT DAMAGE
    - LOCKED OUT RECLOSURE REQUIRES MANUAL RESET
- SUPERVISORY CIRCUITS OVERLAY POWER SYSTEM
  - MONITOR SYSTEMS
  - CONTROL SYSTEMS

* SIMILAR EFFECTS ON LESS SUSCEPTIBLE TRANSMISSION SUBSYSTEM

FIGURE 16 EMP effects on power distribution subsystem (1972 analyses).

Synchronous Stability

- MONITOR/CONTROL CIRCUITS INVOLVE MORE EMP-SUSCEPTIBLE COMPONENTS THAN POWER CIRCUITS
  - SEMICONDUCTOR SENSORS AND SWITCHES
  - COMPUTERS
- GENERATION AND DISTRIBUTION FAULTS PRODUCE WIDE-SPREAD, PERHAPS RANDOM POWER
  - NEEDS (SHORTS, GENERATORS DOWN, ETC.)
  - SURPLUSES (LOADS DISCONNECTED, SHORTED, ETC.)
- FAULTS CAN PROPAGATE FROM ONE AREA TO ANOTHER PRODUCING POWER SYSTEM INSTABILITIES
- RECOVERY AND REDISTRIBUTION ATTEMPTS BY RANDOM CONTROL CIRCUITS THAT SURVIVE WILL UPSET SYNCHRONOUS STABILITY OF SYSTEM: MASSIVE SHUTDOWN

FIGURE 17 EMP effects on supervisory circuitry.

- POWER LOSS DUE TO SYSTEM FAULT

- TRANSIENTS OF 10 - 70 kV

  - SINCE USER CIRCUITS GENERALLY 120 - 480 V TRANSIENTS MORE DAMAGING

- ADDITIONAL TRANSIENTS DUE TO COUPLING DIRECTLY TO USER STRUCTURES, UTILITIES AND COMMUNICATIONS LINES

FIGURE 18 EMP effects on power system users.

- WIDE VARIETY OF TYPES AVAILABLE FOR POWER, CONTROL AND COMMUNICATIONS (INCLUDING RADIO FREQUENCY) APPLICATIONS
  - SIMULATION TESTS VERIFIED PERFORMANCE
- WHEN PROPERLY DESIGNED, ENGINEERED AND MAINTAINED, CAN ALMOST COMPLETELY CONTROL CONDUCTED EMP TRANSIENTS
- SHOULD BE INCLUDED IN INITIAL FACILITY DESIGN AND CONSTRUCTION, AND PERIODICALLY TESTED AND MAINTAINED
- RETROFIT INTO EXISTING FACILITIES POSSIBLE -EXPENSIVE
- ESPECIALLY APPLICABLE TO ELECTRIC POWER SYSTEM MONITORING AND CONTROL FUNCTIONS, INCLUDING GENERATOR CONTROL

FIGURE 19 EMP filters and electronic surge arrestors.

- KEY CHARACTERISTICS OF EMP AND MHD EMP ENVIRONMENTS FROM HIGH-ALTITUDE DETONATIONS AND EMP FROM ATMOSPHERIC DETONATIONS ARE PREDICTABLE
- EMP EFFECTS ON MANY U.S. C^3 AND WEAPONS SYSEMS HAVE BEEN DETERMINED EXPERIMENTALLY; IN GENERAL, UNHARDENED U.S. ELECTRONIC SYSTEMS ARE SUSECPTIBLE TO EMP-INDUCED DAMAGE/UPSET
- ANALYSES BUT NO SIGNIFICANT SIMULATION EXPERIMENTS ON EXTENDED POWER SYSTEMS LEAVES GREATER UNCERTAINTIES IN EFFECTS

FIGURE 20 Summary.

GENERATORS	• SAFETY SHUTDOWN - NUCLEAR PLANTS • TRIP OUT - CONVENTIONAL PLANTS
TRANSMISSION SUBSYSTEM	• LESS SUSCEPTIBLE THAN DISTRIBUTION SYSTEM
DISTRIBUTION SUBSYSTEM	• FAULTS FROM TRANSIENTS AND INSULATOR DAMAGE • RECLOSURE LOCK OUT • SYNCHRONOUS STABILITY UPSET: SYSTEM SHUTDOWN
USERS	• LOSS OF POWER • LARGE TRANSIENTS

FIGURE 21 Summary of anticipated EMP effects.

- OPERATION THROUGH EMP ENVIRONMENTS PROBLEMATICAL

- SHOULD:

  - ASSURE RECONSTITUTION
    - DEVELOP RECONSTITUTION STRATEGY
    - REPLACEMENT COMPONENTS AVAILABLE
    - DISCONNECTING ADJACENT SYSTEMS IF POSSIBLE BEFORE EXCHANGE
    - TRAIN PERSONNEL TO RECOGNIZE & DEAL WITH PROBLEMS
  - UPGRADE PROTECTION AS SYSTEMS BUILT OR MODIFIED
    - STANDARDIZED APPROACHES

FIGURE 22 Recommendations.

BACKUP

"THE RESULTS OF THIS STUDY INDICATE THAT THE ELECTRIC TRANSMISSION SYSTEM MAY BE DISTURBED BY EMP-INDUCED PERTURBATIONS SUFFICIENTLY TO CAUSE MUCH OF THE SYSTEM TO LOSE STABILITY, RESULTING IN A LARGE POWER FAILURE. ALTHOUGH THE EFFECTS FROM EMP ARE COMPLEX, A MODEL WAS DEFINED WHICH SHOULD REASONABLY REPRESENT THE EFFECTS ON THE TRANSMISSION SYSTEM FROM INDUCED PERTURBATIONS ON THE DISTRIBUTION SYSTEM.

BOTH A SINGLE SET AND REPETITIVE SETS OF MULTIPLE FAULTS SEVERLY PERTURB THE TRANSMISSION SYSTEM; THE REPETITIVE SETS OF FAULTS DISTURB THE SYSTEM MUCH MORE SEVERELY. LOSS OF STABILITY OF A SIGNIFICANT NUMBER OF GENERATORS IN THE PERTURBED AREA CAN OCCUR FROM EXPECTED EMP-INDUCED PERTURBATIONS." (R.W. MANWEILER, "EFFECTS OF NUCLEAR ELECTROMAGNETIC PULSE (EMP) ON SYNCHRONOUS STABILITY OF THE ELECTRIC POWER SYSTEM, ORNL-4919, NOVEMBER 1975.)

FIGURE 23 Synchronous stability of the national electric power system: Manweiler's analysis.

"THE MOST PROBABLE EFFECT OF EMP ON A MODERN NUCLEAR POWER PLANT IS AN UNSCHEDULED SHUTDOWN. EMP MAY ALSO CAUSE AN EXTENDED SHUTDOWN BY THE UNNECESSARY ACTIVATION OF SOME SAFETY-RELATED SYSTEMS. IN GENERAL, EMP WOULD BE A NUISANCE TO PLANT SAFETY." (P.R. BARNES, "EMP AND NUCLEAR PLANT SAFETY," NUCLEAR SAFETY, VOL. 18, NO. 3, MAY-JUNE 1977.)

FIGURE 24 Nuclear power plants: Barnes' findings of analysis.

"DURING AN ELECTRICAL STORM ON AUGUST 19, 1980, A LIGHTNING STRIKE IS BELIEVED TO HAVE CAUSED A VOLTAGE SPIKE WHICH BLEW THE FUSE ON INSTRUMENT BUS INVERTERS (1 and 4). THIS CAUSED THE LOSS OF TWO INSTRUMENT BUSSES AND AUTOMATIC REACTOR SHUT-DOWN (at 11:00 pm), SAFETY INJECTION, AND CONTAINMENT ISOLATION. THE REACTOR COOLANT PUMPS TRIPPED ON SAFETY INJECTION AND NATURAL CIRCULATION COOLING WAS ESTABLISHED IN THE REACTOR COOLANT SYSTEM (RCS). AT 1:15 am ON AUGUST 20, 1980, THE RESERVE AUXILIARY TRANSFORMER TRIPPED AND AN ELECTRICAL FAULT AND FIRE WAS REPORTED ON THE ALUMINUM BUS BARS BETWEEN THE RESERVE AUXILIARY TRANSFORMER AND THE 4160V BUSSES 1-1 AND 1-2. THE PLANT FIRE BRIGADE RESPONDED AND VERIFIED THAT WHATEVER FIRE HAD EXISTED WAS EXTINGUISHED. THE LOCAL FIRE DEPARTMENT WAS NOT REQUIRED." ("PRELIMINARY NOTIFICATION OF EVENT OR UNUSUAL OCCURENCE -- PNO-111-80-156A," AUGUST 21, 1980.)

FIGURE 25 Nuclear power plants: A lightning event at the Kewaunee site.

"THE CAUSE OF THE REACTOR TRIP/SAFETY INJECTION (ON JUNE 9, 1980) WAS A LIGHTNING STRIKE WHICH APPARENTLY PENETRATED THE ZONE OF DIRECT STRIKE PROTECTION AND STRUCK IN THE VICINITY OF THE CONTAINMENT BUILDING AT THE SOUTH PENETRATION AREA. WE BELIEVE THE STRIKE HIT #2 AND #14 MAIN STEAM VENT PIPES WHICH EXTEND ABOVE THE PENETRATION AREA ROOF AND THE SURGE WAS CARRIED INTO THE BUILDING VIA PIPING CONNECTIONS. THE LIGHTNING INDUCED TRANSIENTS SIGNALS FROM FOUR PRESSURE TRANSMITTERS IN THE SOUTH PENETRATION AND ONE TRANSMITTER IN THE NORTH PENETRATION AREA, COUPLED WITH THE FAILURE OF THE TWO TRANSMITTERS WAS SUFFICIENT TO COMPLETE THE SAFETY INJECTION LOGIC.

NO. 13 AUXILIARY FEED PUMP OVERSPEED TRIP WAS CAUSED BY A BROKEN GOVERNOR FEEDBACK LINKAGE GUIDE PIN. GOVERNOR CONTROL WAS LOST AND RESULTED IN OVERSPEED.

THE REACTOR COOLANT SAMPLE WAS DELAYED DUE TO A DIAPHRAM FAILURE OF ICV227 REACTOR COOLANT LETDOWN LINE ISOLATION VALVE ACTUATOR. THE VALVE FAILED IN THE FAIL-SAFE POSITION, CLOSED." (ATTACHMENT 1 TO "ECCS ACTUATION REPORT NO. 80-31/99X". JULY 8, 1980)

FIGURE 26 Nuclear power plants: A lightning event at Salem Generating Station Unit 1.

EMP DEFENSES

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Defense Nuclear Agency
Washington, D.C. 20305

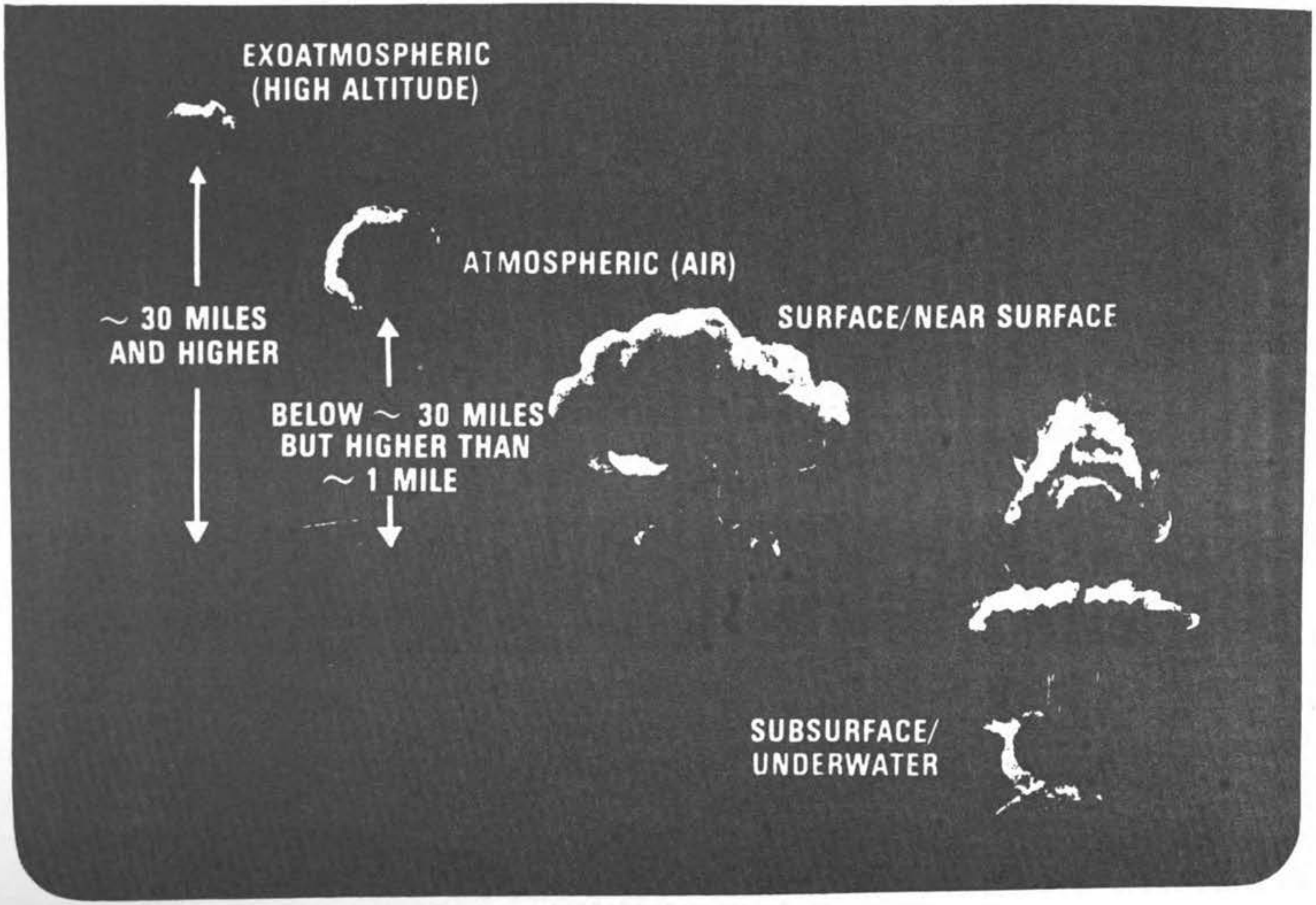


FIGURE 1 Weapon detonation options.

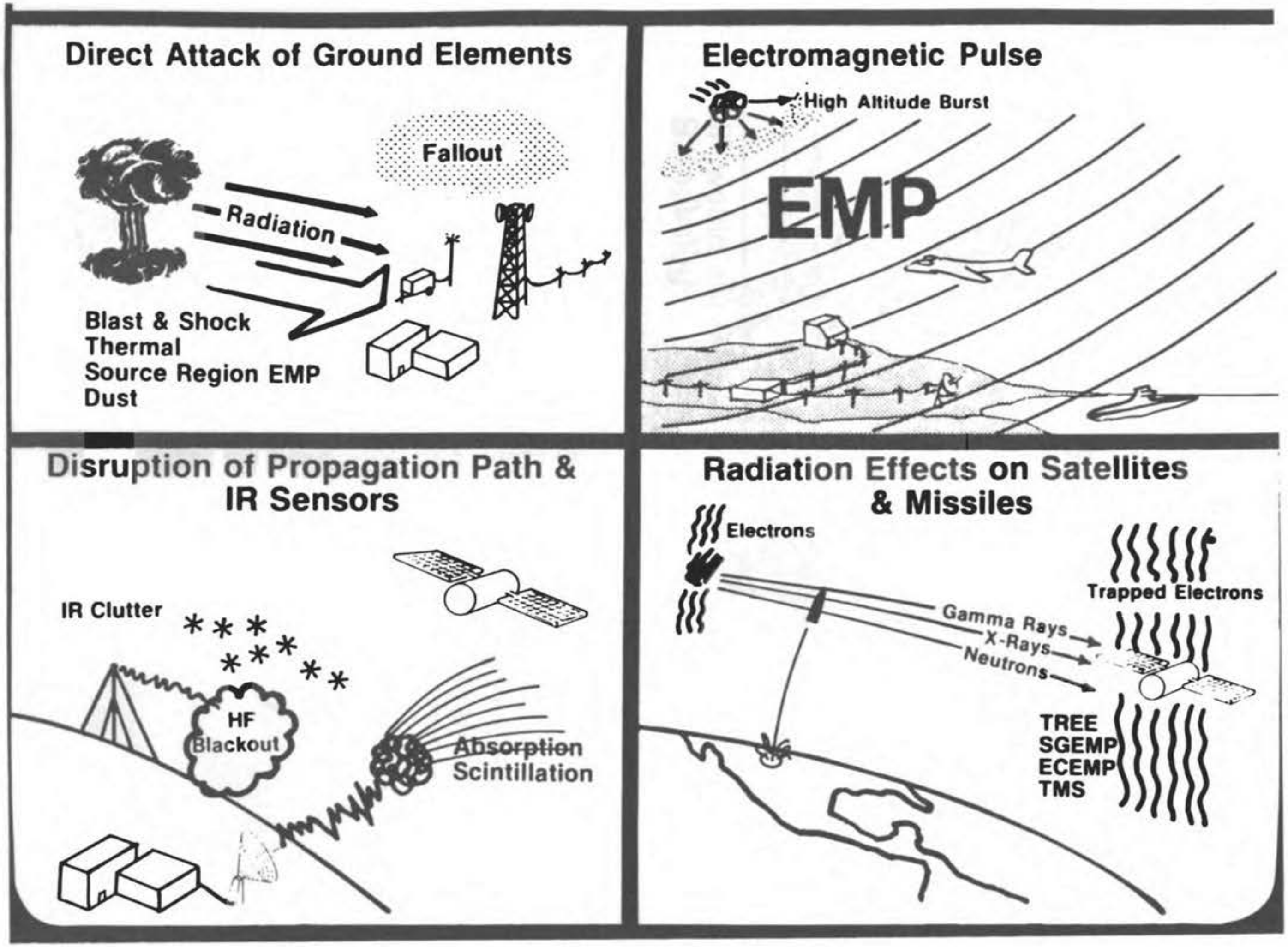


FIGURE 2 Nuclear weapon effects.

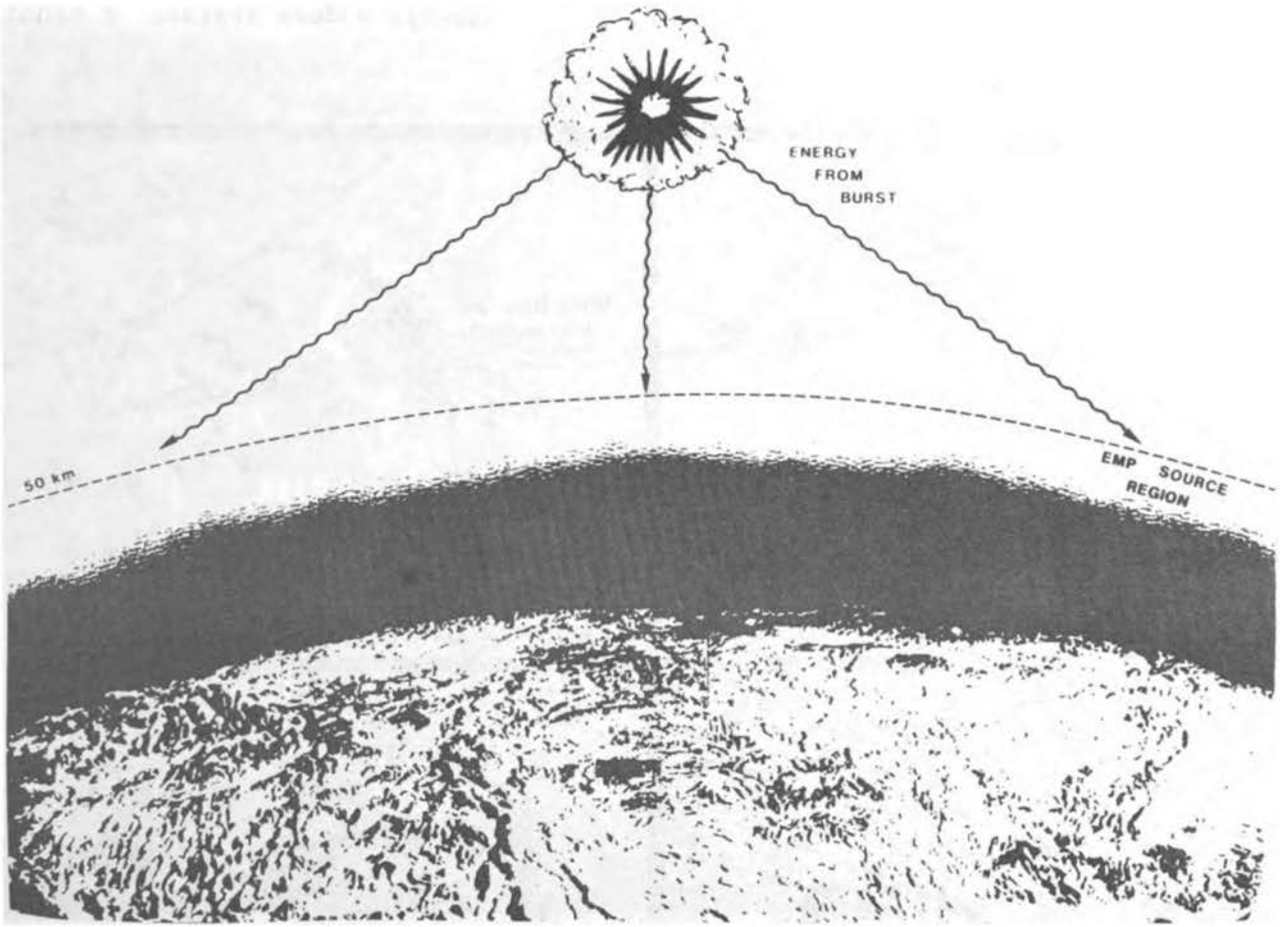
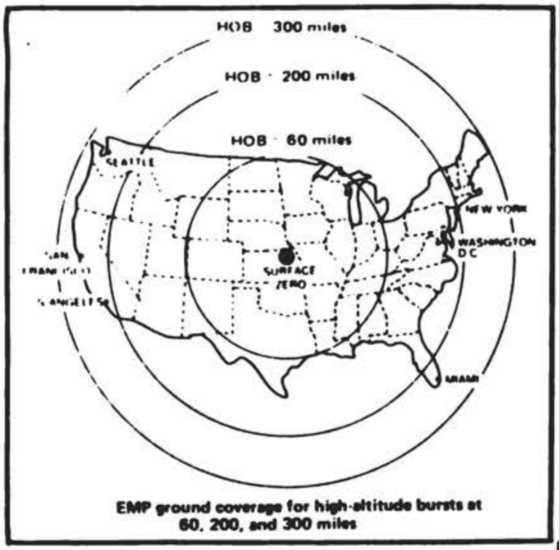
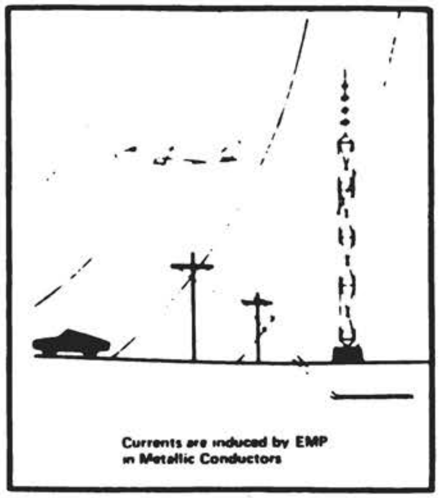


FIGURE 3 High altitude EMP generation.

Coverage



Collectors



Effects

- EMP would affect systems, facilities & networks throughout the U.S. inducing damage & upset to electrical systems
  - Extent of damage & upset caused is unknown — difficult to assess in all but few cases
  - National implications for military or civilian sector have not been assessed
  - EMP caused damage/disruption is recoverable with adequate planning, time, spare parts & trained manpower

FIGURE 4 EMP.

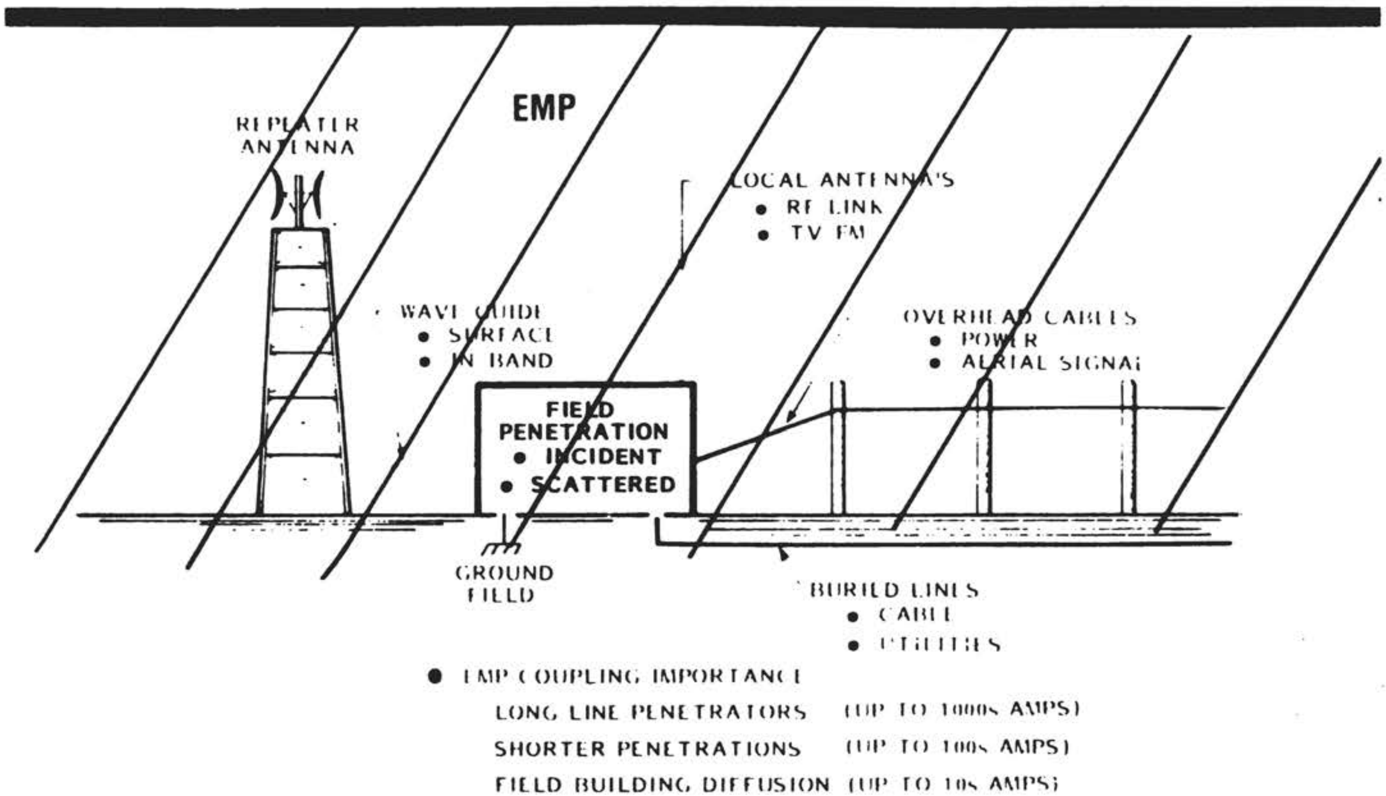


FIGURE 5 HEMP coupling to typical "landline" facility.

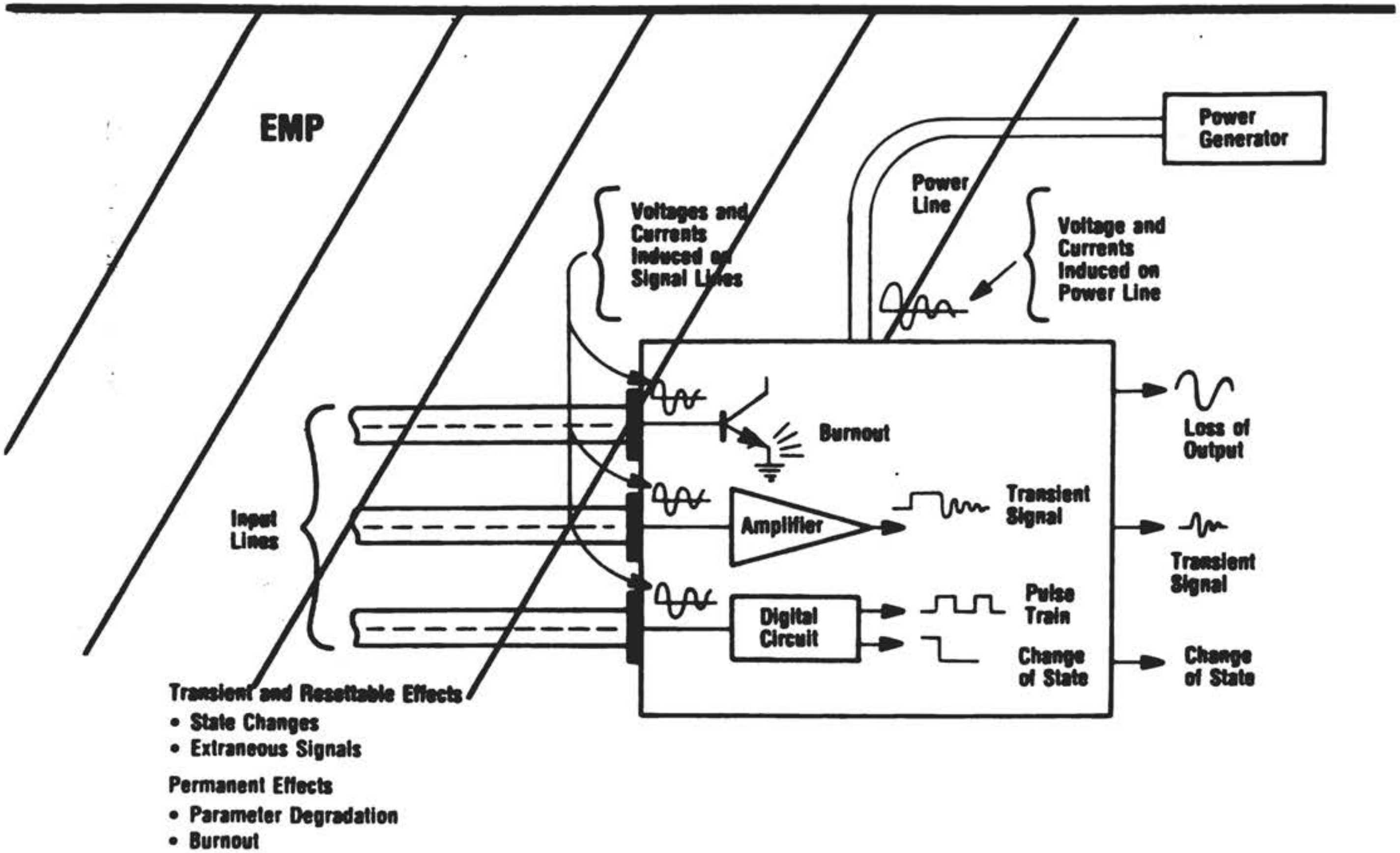
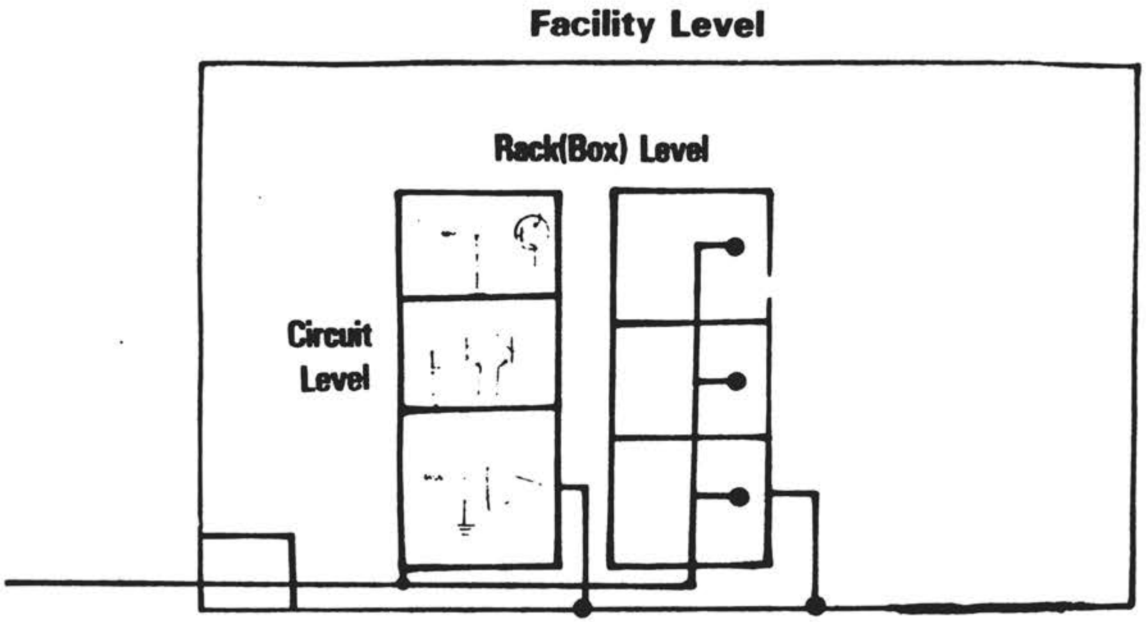


FIGURE 6 Effects of EMP on electronics.

FIGURE 7 Riddle: How many missiles does it take to put out all the light bulbs?

- Hardening
- Operational Procedures

FIGURE 8 Response to high altitude EMP effects.



Facility Level Practices

- Continuous external facility shield
- Shielding incoming power/ C^3 lines
- Facility grounding
- ESA vault at antenna/line penetrations
- Fiber optic C^3 lines

Rack Level Practices

- Rack/box shielding
- Cable shielding
- Current limiters at box terminals
- Ground plane
- Cable routing

Circuit Level Practices

- Choice of robust piece-parts
- Common mode rejection
- Circumvention/reset

FIGURE 9 Hardening: Lines of defense.

HARDENING SHOULD NOT BE DONE ON AN INDIVIDUAL SYSTEM BASIS, BUT SHOULD ADDRESS A HARDENED MISSION CAPABILITY WHICH THEN REQUIRES HARDENING A NUMBER OF SYSTEMS SUPPORTING THE MISSION.

FIGURE 10 EMP hardening.

Educate

- Recognize effects
- Response options

Prepare

- Response options
- Back-up equipment
- Equipment layout
- Electrical isolation

FIGURE 11 Operational procedures.

- Systems which are electromagnetically simple — small in size with small number of EMP penetrations — *can* be made *demonstrably survivable* to HEMP

- As system size, complexity & number of EM penetrations increases, difficulty in performing EMP assessment increases rapidly

- Reliable EMP hardening & assessment require simple EM geometry in order to demonstrate survivability
  - Separation into physically tractable units
  - Enclosure in topologically continuous shielding
  - Minimization of EM penetrations
  - Isolation of penetrations at shielding

- Cost experience
  - For new systems, EMP hardening costs ≈ 1—2% of acquisition
  - For existing unhardened systems, EMP hardening costs ≈ 5—10% investment

FIGURE 12 EMP hardening summary.

RELIABILITY, RESEARCH, AND EFFICIENCY

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In thinking about the subject of this paper, I was reminded of a paper delivered 30 years ago almost to the day--on April 22--before the Oak Ridge, Tennessee, section of American Institute of Electrical Engineers (AIEE) by the late Philip Sporn, then President of American Electric Power Company and one of the great technological leaders in the history of the electric utility industry. The title of the paper was "Perils and Profits of Pioneering." In the paper Sporn recounted the difficulties encountered by his company, including unexplained equipment failures, in the course of developing such major technological advances in electric power generation as supercritical temperature and pressure technology and extra high voltage (EHV) transmission. He also described the ways in which those difficulties ultimately were resolved through the combined application of research, engineering, and the empirical analysis of in-service experience.

It occurred to me that had those events he described occurred in the present environment, generation and transmission technology might now still be back where it was at the end of World War II. We are here to discuss the directions in which efforts ought to be channeled to ensure the continued availability of a reliable, economically efficient electric power supply system; yet we have at the same time created, in the past decade or so, an institutional environment tending to suppress incentives for technological research and--at least in the electric utility industry--innovation. We seem to be increasing the perils steadily while the profits become increasingly difficult to find.

The ultimate test of the validity of research results is the implementation of the research findings on an operating electric utility system. A system undertaking the implementation of a newly developed technology confronts the risk that the new technology will not perform as expected or will pose problems in the transition from laboratory to application. Resolution of those problems may require an extended period of time and may impair effective system operation, at least initially. Such problems are inherent in any effort to push forward the technological boundaries.

To this risk must now be added the prospect that performance inadequacies will incur penalties by the regulatory agencies in the rate-making process, which serves to discourage the technological risk taking without which new technology to achieve greater reliability and lower cost cannot be developed and diffused throughout the industry. This is not to say that regulatory oversight is not desirable to ensure that utilities do not undertake imprudent expenditures or perform incompetently. But some mechanism must be found to balance regulatory oversight with the encouragement of prudent technological risk taking and innovation so that efforts to improve performance by extending the technological frontiers are not suppressed. Perhaps there is a need for more dialogue between utilities and regulators, dialogue that could provide for advance approval of a utility program to test specified new technologies. At present, the incentives, especially the regulatory incentives, are designed to encourage the continued application of well-established conventional technology. This may in part explain the relatively static technological performance of the electric utility industry over the past decade. For example, thermal efficiency has shown no improvement. In 1973 the industry's heat rate was 10,429 Btu per kWh and in 1983 it was 10,539 Btu per kWh, equivalent to an increase of some 30 million additional barrels of oil to provide the fossil fuel-fired generation in 1983. It may also explain the industry's great interest in standardization.

Standardization may be appropriate in some circumstances. For example, it is very helpful to standardize the various steps in transmission voltages. It is important, however, that care be exercised to prevent standardization from becoming the excuse for avoiding technological risk and slipping into technological obsolescence. Between 1900 and 1920 the electric utility industry had about doubled its thermal efficiency and might have standardized on the generating technology of that period, but it would have sacrificed the further doubling in thermal efficiency that was subsequently achieved through advances in temperatures and pressures. Or the industry might have settled many years ago on the well-established 138 kV transmission technology as the maximum transmission voltage rather than pushing the technology forward to 345 kV and 765 kV. If it had, the countryside would now be crisscrossed with a great many more transmission towers, and line losses would be significantly higher. There might be fewer regulatory hearings on the biological effects of transmission lines, but there would certainly be no dearth of hearings on the environmental and aesthetic impacts of the multiplicity of lower voltage transmission lines the industry would now be required to build. In short, while standardization may have its appropriate place, it should not deter and stultify technological innovation that has the potential for further enhancing the reliability and economic efficiency of this nation's electric utility systems.

Surely there are now sufficient deterrents to technological progress in the electric utility industry without creating additional institutional barriers. The slowing in the industry's rate of growth together with the very substantial increase in construction lead times have already contributed to the slowing of technological advances and their dispersion throughout the industry. With slower growth and less construction there are fewer opportunities to apply and test new technology and, if proven successful, broaden its application throughout the industry. Indeed, even if a utility can overcome the pressures that tend to discourage technological risk taking, the lead times between initial design and the completion of construction are now so great that a new facility may incorporate a new technological advance that could by the time of completion already be obsolete. Furthermore, the time required before a new technology can pay off its developer has also been extended since more time is now required between development and testing and between testing and wide industry dispersion. Thus, the incentives for research and development are diminished for both the utilities and the manufacturers who, acting together with the utilities in the past, pushed forward the industry's technological frontiers.

A possibly more insidious and too easily ignored effect of these forces is that the electric utility industry--historically less than successful in attracting the very best technologists--may now have even more difficulty. Moreover, the manufacturers also may now have difficulty in attracting the highest quality engineers (and supporting those they do attract) to work on power supply problems, research, and equipment development.

Finally, the cost of exploring new technological avenues, and especially the very high risk of testing new technologies on an operating system, may now have become so great that only a very few of the largest systems can afford such efforts even under the best of circumstances. In the past the cost of introducing a new technology was not so high (relative to average embedded costs and to a utility system's total capital) that failure would threaten its financial integrity. Even a prototype nuclear generating unit might have cost only 40 to 50 percent more than the average embedded cost of existing generating capacity or the cost of a new conventional fossil fuelfired unit. In addition the marginal cost of replacement energy was not overwhelmingly high relative to average generating costs. Furthermore, costs (and rates) were declining. At the present time these conditions have reversed. The result is greatly increased risk associated with testing a new technology, which is further compounded by the resistance to rate increases to cover the costs of incurring such risks in this era of rising consumer electricity prices. It may, therefore, be necessary to increase institutional structures to permit wider sharing of risks among many utilities through joint project participation. Joint arrangements among several utilities and a manufacturer comparable to those employed for the construction of some of the early experimental and prototype nuclear generating units may be required to encourage more technological risk taking on the part of electric utilities.

According to the Program Information Notice issued in October 1984 by the U.S. Department of Energy, Office of Energy Systems Research, the purpose of its research program "is to support the development of an electric network which will enhance regional energy exchanges, optimize controllability of all electric energy sources, and enhance essential service continuity especially during local, regional and national emergencies." According to the information notice, the research projects, classified under "Normal/Emergency Operating Concepts," will contribute to the competitive position of U.S. firms, and produce a substantial increase in productivity...." There is no further discussion of how the existing research program will promote these laudable objectives.

Over the last decade the electric utility industry in the United States has approximately doubled its investment in transmission and has greatly expanded transmission capability. Between 1972 and 1982, the industry increased the circuit miles of transmission 132 kV and higher by almost 55,000 miles, or 35 percent, while total kWh generation increased only 28 percent. About half of this added transmission was at extra high voltage levels of 330 kV or higher. This large, more than appropriate increase in EHV transmission indicates that transmission capacity has been increased by substantially larger magnitudes than the increase in circuit miles alone would suggest. Nevertheless, the concern remains that transmission inadequacies are impairing the ability of utilities to transfer large quantities of economical power from areas of surplus low cost power supply to areas of high cost or inadequate capacity, thereby jeopardizing power supply reliability, denying consumers lower cost sources of power than they now have available, or both. Transmission limitations on interregional power transfers, it is alleged, may even be the cause of constructing additional generating capacity that otherwise might not be required. The research program described in the information notice appears to be based on these assumptions, which must be reexamined if an effective, relevant long-term research program is to be implemented. There may be areas of the country in which transmission capacity limitations are restricting interregional power transfers below the maximum levels that existing generating capacity might otherwise make possible. The limitations are not, however, imposed by inadequate technology but rather by institutional and economic issues.

Electric power transmission is an expensive form of energy transportation. It has been made even more expensive by the large increase in fuel and generating capacity costs over the past several years that has greatly increased the cost of transmission line losses. A 765-kV transmission line with a transfer capability of perhaps as much as one million kilowatts when fully loaded may cost in the neighborhood of one million dollars per mile, depending upon the cost of rights-of-way, population density, terrain characteristics, and other local factors. Thus a 300-mile line may cost $300 million and incur annual fixed charges, including operation and maintenance, of about $60 million. If the line could be fully loaded during each hour of the year (a highly unlikely operating condition), it would transfer 8,760 million kWh. The annual fixed charges would amount to 6.8 mills per kWh or the equivalent of 65 to 70 cents per million

Btu. The energy value of the line losses would increase the cost by 2.5 to 3.0 mills per kWh, equivalent to 25 or 30 cents per million Btu, and the capacity value of the line losses could add another 1.5 mills, or 15 cents per million Btu, to the cost.

Thus, to justify construction of such a line for the interregional transfer of energy could require a fuel cost differential of about $1 per million Btu, equivalent to about $25 per ton of coal or $6 per barrel of oil. This gives no consideration to other costs that may be necessary to ensure reliability, including alternative transmission routes, strengthening of the internal transmission of the receiving system and the intervening systems, and the need for generating reserves on the receiving system.

Interregional fuel cost differentials of this magnitude have been unusual in the United States. The apparent increase in the economic viability of long distance interregional transmission in recent years has resulted largely from the combined efforts of the increasing constraints on viable power plant sites; the changes, seemingly relatively short term, that have occurred in the structure of fuel markets over the last decade (especially the sharp increase in oil prices); and the regional distribution of surplus generating capacity resulting from the completion of long lead time generating capacity, construction of which was begun prior to the substantial decline in the rate of load growth that began with the OPEC oil embargo.

The long-term persistence of these conditions is questionable, at the least. Oil prices (and the prices of gas and coal) have already shown some decline. As electric energy use continues to grow and reduce the existing generating reserve margins, the availability of generation for interregional transfers will also decline. This leaves only the constraints on power plant sites as a factor causing a need for long distance interregional power flows. And even this remains in doubt, depending, as it does, upon whether future development of power supply continues on its historic path of large central station power or whether this trend is reversed to emphasize small dispersed power supply sources. Thus, the long-term economic opportunities for long distance interregional power transfers may be far fewer than they now seem. And the thrust of long-term research efforts may yield more useful results if redirected from the needs of large bulk power supply systems to those of widely dispersed systems relying on small on-site power supply sources.

Where opportunities for economically viable interregional power transfers arise but are inhibited by transmission limitations, the cause is not to be found in present technological inadequacies. Rather, it is to be found in the uncertainties surrounding the long term economic viability of a bulk power transmission system designed to facilitate such transfers.

The sharp increases in oil and gas prices and the accompanying supply stringency during the latter half of the 1970s was a major factor in attracting attention to the need for interregional power transfers. However, just as attention is turning to making possible greater capacity for such transfers, oil and gas prices are falling and supplies are in surplus, thereby reducing the economic incentive. At the same time electric utility systems have greatly curtailed their construction programs to permit their loads, even at presently slower growth rates, to expand into the capacity already on line or nearing completion. Thus, within four or five years (less than the time required to construct additional transmission capability) the capacity available for interregional transfers can be expected to fall sharply. Finally, while suitable sites for new large generating capacity may continue to become increasingly difficult to find, they may also become less urgently needed if loads continue to grow at the present rate, which is much below historic long term growth rates, and especially if the large central station becomes obsolete, as some would suggest.

Institutional pressures and incentives at present appear to be encouraging the development of relatively small, widely dispersed power supply sources rather than large central station service. As--or if--cogeneration, small hydro, photovoltaic devices, and other onsite power sources under development become an increasing share to total power supply, they may have a profound effect on the development and function of the large central station system--in particular, its transmission system. The long-term implications of these developments need to be given greater attention.

The design of a long-term research effort to allocate limited research resources among competing research alternatives requires that an effort be made to answer, at least tentatively, some of the fundamental questions surrounding these issues. Efforts must also be made to visualize the structure of the power supply system as it may develop or as we may want it to develop over the next two or three decades.

The electric utility industry until recently has been characterized by a relatively stable high rate of growth and technological efforts to exploit economies of scale. At present, load growth appears to have become far more erratic and slower, and the incentives appear to be toward a reversal of those historic technological trends in favor of an emphasis on small, onsite dispersed power supply sources. Whether this will result in a more or less efficient, more or less costly, more or less reliable power supply system, especially under defense emergency conditions, remains to be determined. The technological opportunities for achieving improved reliability and lower costs for the existing systems, compared with those for changing direction to the small dispersed power supply system, still need to be evaluated, as do the research requirements under either scenario. It may well be that a competitive research effort to hedge both alternatives is desirable. Whether the existing transmission system will require expansion at still higher voltages, or whether it can be allowed to remain as is or even to atrophy, will determine the direction research efforts must take. Such efforts can either continue in historic directions requiring further expansion of transmission capacity and research to develop higher voltages and/or superconductors--or change to develop small, relatively isolated power supply sources with, perhaps, some large capacity transmission to be maintained in an essentially standby mode for emergency service. Whatever the particular course of research and development efforts, their objective is the same: to make a relevant contribution to a reliable low cost power supply for this nation two or three decades from now.

Effective operation and maintenance of a power supply system can make some small contribution to reliability and economic efficiency. The fundamental determinant of power supply reliability and economic efficiency, however, is the effective integrated system design, beginning with fuel supply and extending to the point of consumption. Long-term fuel supply and prices, the location and design characteristics of the fuel conversion systems, and the integrated movement of the resulting electrical energy to the point of consumption (taking into account the characteristics of the consuming devices, including energy storage) must be analyzed and evaluated. Such an evaluation will determine how effectively a research program will contribute toward the attainment of a future power supply system that will provide the desired reliability at the lowest possible cost.

In summary, greater attention to research to improve our understanding of the economic and social forces affecting the growth and development of the electric power industry is needed. We must attempt to visualize the power supply system as it may evolve or as we may want it to evolve over the next two or three decades. Then it will be possible to shape a meaningful and effective long term research program capable of providing the technological tools with which to enhance the reliability of the nation's future power supply network and to improve the efficiency of electric energy delivery systems.

RELIABILITY: HOW WILL IT BE PRICED AND HOW WILL WE PAY FOR IT?

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INTRODUCTION

Very little attention is paid in the electric utility industry today to the explicit pricing of reliability. Current circumstances, such as the increasing availability of independently produced power (third-party generation), and new regulatory trends, such as the treatment of conventional generating units on a par with third-party generation, point to the increasing importance of explicit policies that will lead to more economically efficient reliability choices. Such policies will help avoid the repetition of current planning debacles. These policies have implications for electric utility planners and suggest areas in which research will offer benefits in obtaining more efficient and economical electric energy systems.

CURRENT PRACTICES AND NEW TRENDS

Current electric system reliability standards have evolved over time as standard industry practice without being subject to a great deal of analysis. For example, the bulk generating system reliability standard is usually taken to be "one day in ten years" (i.e., there should be generating capacity so that a capacity shortfall due to outages of generating units would occur only one day over a ten-year period). This criterion has been found to be excessive by a factor of two, at least as an operating standard (Telson, 1975). (A planning standard may have different implications. See Electric Power Research Institute, 1978.) There do not appear to be explicit standards for transmission and distribution system reliability, although transmission and distribution system failures account for all of the outages experienced by California electric customers (California Public Utilities Commission, 1982).

Thus, the level of reliability built into electric systems has been the result of the relatively unexamined actions of electric utility planners, even when industry standard practices have been adhered to. These industry standard practices have not been subject to critical examination.

Pricing practices for reliability also have received little attention. Although large electric customers typically are billed for a capacity component as well as for energy use (through the use of "demand metering"), this charge often has little relationship to the actual cost of reliability. This can lead to tremendous economic inefficiencies. For example, currently in California, municipal utilities that buy power from the large investor-owned utilities pay for it according to rates set by the Federal Energy Regulatory Commission. The "demand charge" (the charge per kilowatt for each municipal utility's monthly peak demand) is based on the average capital cost of the investor utilities' plants. Thus, although there will be a capacity glut from the addition of new baseload nuclear generating facilities, the entire capital cost of these facilities is loaded onto the demand charge. This prompts the municipal utilities to build peaking facilities to meet their own peak loads and avoid the demand charges. The result: While there is no need for new generating capacity within the state, and there is an increasing amount of low-fuel-cost electricity available, municipal utilities throughout the state are building gas turbine generators.

No doubt there will be a response to this situation. Rather than raising rates in this manner, and then losing revenue as customers leave the system, the investor utilities can revise their rate structures.

A similar situation, and a similar response, has already occurred in California with regard to third-party generation. The Public Utility Regulatory Policies Act, better known as PURPA, requires that utilities pay an approximation of market price--avoided cost--for power generated by independent producers, such as industrial cogenerators. These avoid-cost rates led to such an outpouring of cogeneration proposals (and, indeed, signed contracts to sell power to California utilities) that one of the avoided-cost tariffs was recently suspended. The fear now is that too much cogeneration will be forthcoming, and as a result avoided costs will be dramatically lower than previously estimated.

The regulatory trend, then, is to set rates to follow marginal cost more closely. Although setting rates equal to marginal cost has been an avowed goal for some time, the very real planning consequences--whether or not several thousand megawatts of third-party generation are developed--puts real teeth into the marginal cost principle.

There is, however, another factor that may accelerate this trend. There is a possibility that PURPA-style pricing could be applied to new utility-owned generating units, as well as to third-party units. The reason for this is to avoid protracted arguments about the need for newly constructed facilities and the prudency of expenditures on these plants. If the plants are indeed cost effective, as the utilities claim, then they should be willing to accept marginal cost revenues for their investment.

There would be many economically beneficial effects of such a policy. In the near term the most important effect is probably that utilities and potential cogenerators would no longer be at complete odds over the issue of setting avoided-cost rates. (Until now, for obvious reasons, utilities have favored low rates, while cogenerators favored high rates.) In the longer term, the most important implications are for planning. Again, a policy that applies the marginal cost pricing principle to all new generation makes it important that prices are set correctly. The price of reliability is an important component of marginal cost prices.

PLANNING IMPLICATIONS OF NEW REGULATORY POLICIES

Utility planners who plan under a marginal cost pricing regime (like industrial planners throughout unregulated U.S. industries) must pay close attention to matching expenditures on increased capacity with the economic value of that capacity. The costs and benefits of a new plant investment are easy to enumerate: The costs are the capital costs of the new plant and the fuel costs of running it. The benefits are the savings in fuel costs of other plants and the value of reliability increases (compared to the situation where the plant is not built). Only the last element, the value of reliability increases, has any degree of controversy associated with its measurement. The economically correct solution is simple: set prices equal to short-run marginal fuel costs plus a rationing charge at all times, and measure the fuel-cost benefits by this marginal cost price. (The rationing charge is the price that will balance the demand for on-peak energy with the supply.) Although simple, this solution is also alien to most utility planners. An acceptable substitute, already familiar to most people in the industry, is to use the capital cost of a combustion turbine plant, applied to on-peak energy and capacity prices, as a proxy for the value of reliability.

Thus, the question the utility planner under a marginal cost planning regime must ask is simple: Will the revenues from the proposed new plant, where these revenues are determined by selling its output at marginal cost prices, cover the capital and fuel costs of the plant? The answer, of course, is not so simple to find. It never has been, but, in the past, utilities never asked the question at all. Under previous regulatory regimes, utilities were guaranteed cost recovery of their expenditures. Planners built to meet a given reliability standard. ("We are required to meet our customers needs.") Prices would be equal to whatever the resulting costs turned out to be. If that cost turned out to be higher than the price customers were willing to pay, cost recovery continued anyway, and the prices departed from marginal cost.

A marginal cost planning regime does not make the utility planners' job easier. What it does is offer strong incentives toward increased efficiency in meeting customer needs, and toward new approaches to meet these needs.

RESEARCH GEARED TO SYSTEM PLANNING UNDER NEW REGULATORY REGIMES

It has been clear for some time that the inherent risks of conventional planning options--large central station generating plants--are too great. A marginal cost planning regime simply makes this fact crystal clear. But there are options, some that are currently available and others that are in development, that can reduce the risks of utility planning.

Demand-Side Investment

Utilities that actively participate in construction "on the customer's side of the meter" have an additional tool with which to control and direct growth in energy consumption. This is a currently available option, as experience by utilities across the nation has shown, most notably in California, New England, and Florida. Demand-side investments have lower risk in two important areas: the certainty of performance (it is unlikely that conservation devices will all fail to work or will all be delayed significantly); and the certainty of financial return (conservation investments are made in small pieces, which begin "producing" energy within a relatively short period of time). Demand-side investments also offer a method of inexpensively producing increases in reliability. For example, more efficient refrigerators and air conditioners and off-peak air conditioning through thermal storage all offer more reliable and less expensive means of increasing reliability.

Integrating Small Power Production into Utility Systems

Cogeneration and other forms of "small" power production are known technologies of increasing importance. More research is needed, however, on integrating these generating sources into existing generating systems, especially in terms of planning. What is the contribution of a large number of relatively small, dispersed generating sources to system reliability? Even if each generator is relatively unreliable, the sum of their output may make a very reliable and predictable contribution to system reliability. What is the correct price to offer for such "individually non-firm" but "collectively firm" power? Too often the utility price offer has been zero.

Paying for Reliability

New technologies can help resolve the question of the value of reliability on both the generation side and on the demand side. On the demand side, more sophisticated meters can offer real-time pricing schemes. By charging prices that reflect variances in these costs through the day and between days and seasons, customers will have better information and greater incentives to make cost-efficient decisions with regard to electricity use.

Similarly, if such real-time prices were offered to independent power producers, they would have proper incentives to maximize the operation of their facilities when their operation was of the greatest use to the electric system.

Microcontrol

A step beyond real-time pricing is technology that will offer customers the ability to make real-time responses to real-time prices. Arthur Rosenfeld has described experiments currently underway in England to develop a microprocessor-controlled metering and load control system for domestic use (Rosenfeld, 1985). One hundred fifty units have been put through successful trials, and widespread application is planned. These meters, called Credit and Load Management Units (CALMU) receive radio broadcast signals of electricity prices. This price is "transponded" by power-line carrier signal to switch boxes connected to major appliances. These switch boxes can be preset to interrupt the operation of that appliance when the price reaches a preset level.

The CALMUs also are designed to provide automatic meter reading by telephone and are projected to pay for themselves with this application alone. An example of the load management capability of such a system is for emergency load shedding. The CALMUs make it possible for each refrigerator to be shut off for a short period of time. Rosenfeld estimates that the statewide load reduction in California in such a case would be in excess of 1,800 MW.

CONCLUSION

A trend is developing in electric utility regulation as a result of real-world events. The trend is toward more responsive and realistic electricity prices--viewed from both sides of the meter. Customers will be paying the full costs of electricity in a manner closely related to the costs they actually incur, and utilities will receive the full value of electricity produced, but only as such value is actually created. This precludes cost recovery on "unneeded" plants, but promotes value recovery for those plants that are indeed valuable.

The trend is a result of the increasing availability of third-party generation, such as industrial cogeneration, and a regulatory and utility desire to avoid protracted arguments about the need for newly constructed power plants or the prudency of expenditures on these plants.

This new regulatory policy--of marginal cost pricing for both customers and the utility--will be impossible to live with if utility planners insist on following traditional paths. But there are available and emerging technologies that offer the flexibility and reliability necessary to cope with the new problems. Research to accelerate the development of emerging technologies can ease the transition to a more competitive and efficient electric utility industry.

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NORMAL/EMERGENCY OPERATIONS: UTILITY NEEDS AND EXPERIENCE

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INTRODUCTION

The purpose of this paper is to discuss experiences in operating a complex electric energy system and, based on this experience, present a list of needs that could enhance the reliability and economic operation of power systems during normal and emergency operation. The Mid-Atlantic Area Coordinating (MAAC) Group system, one of the nine North American Reliability Council (NERC) regions, is the referenced system.

The paper focuses on the desire to enhance regional energy exchanges while maintaining acceptable levels of service reliability during normal and emergency conditions.

BACKGROUND

The MAAC system is one of nine NERC reliability councils. It includes electric power systems in the states of New Jersey, Pennsylvania, Maryland, Delaware, Virginia, and the District of Columbia. Figure 1 shows the geographic location of MAAC.

The following summarizes the MAAC system characteristics based on 1984 operations. System peak load was about 35,337 MW, with installed generating capacity of about 47,063 MW. The net annual energy supplied by MAAC was 184,851 GWH. The mix of MAAC installed generation was as follows: nuclear, 18.1 percent; hydro, 4.6 percent; coal, 27.5 percent; oil and gas-steam, 32.7 percent and oil and gas.ct, 17.1 percent. Energy production by fuel type was as follows: nuclear, 18.2 percent; coal, 51.5 percent; hydro, 3.1 percent; oil and gas, 15.1 percent; and interchange, 12.1 percent. The voltage level of a MAAC bulk power transmission system is primarily 500 kV and 230 kV. There were about 1,600 circuit miles of 500 kV and 4,600 circuit miles of 230 kV in service in 1984.

MAAC is unique in that the reliability council closely corresponds to the power pool that coordinates operation of the member companies'

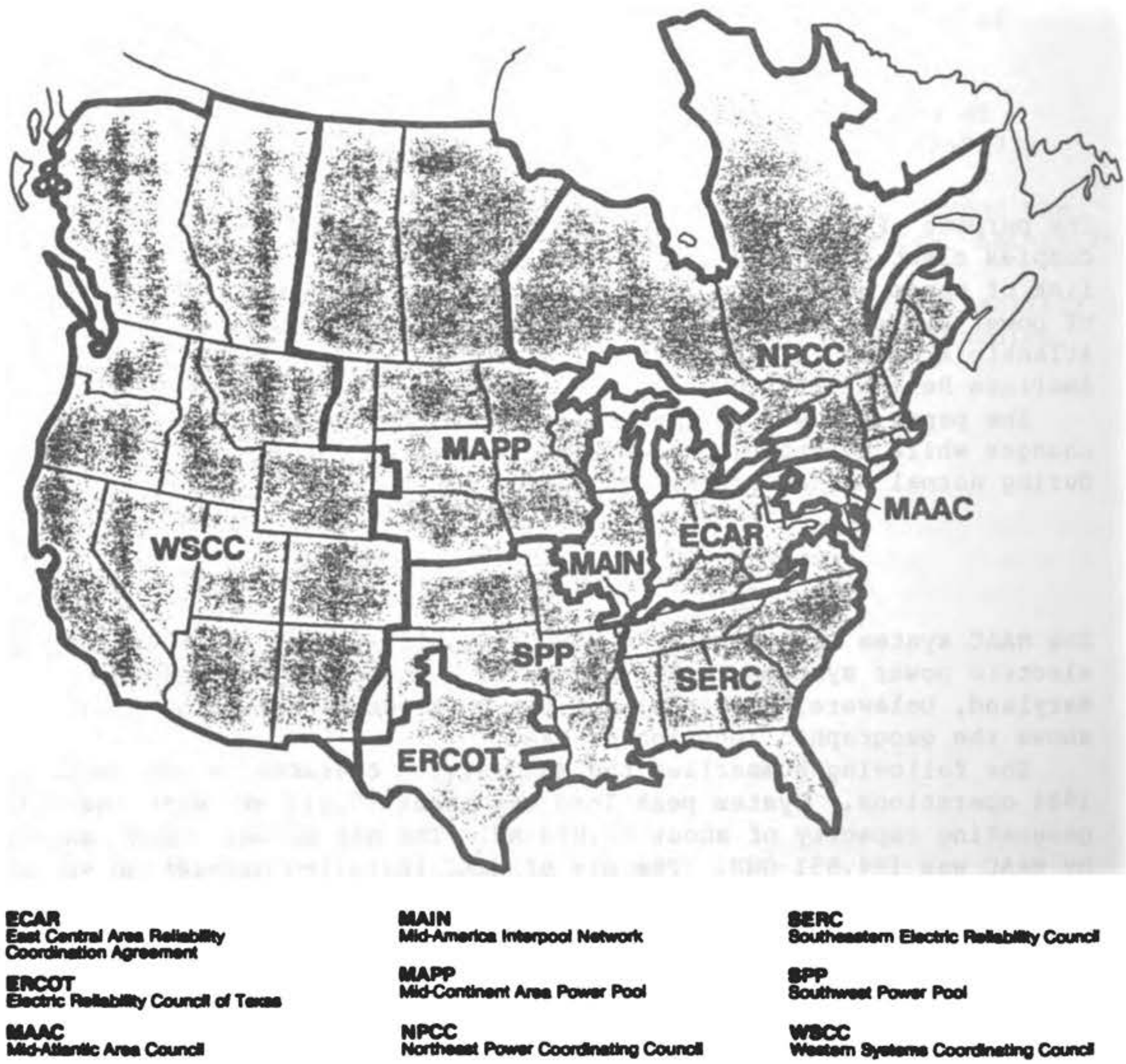

FIGURE 1 North American Electric Reliability Council.

electrical systems. The Pennsylvania, New Jersey, Maryland Power Pool (PJM) coordinates system operation from a central control center by operating as a single control area. PJM operations include scheduling the member companies' generation at the same incremental cost level on a pool basis and monitoring and controlling transmission system loading to ensure safe system operation.

The existing bulk power system in MAAC was primarily developed according to reliability principles and standards. Most of the 500 kV transmission system was built to deliver baseload generation from remote sites to load centers. Major interconnections to other regions were built to reduce the requirement for generation reserve since help from neighboring systems could then be received during capacity emergencies. Some economy transfer took place, but in small amounts because fuel price differences were not great. The system designed for reliability provided more than adequate capability for economy transactions.

In the 1970s, several changes took place that had a major impact on the operation of the system. Fuel price differences between oil and coal increased significantly. The result was a strong incentive to minimize use of oil by delivering coal-generated energy over the transmission system. Also, load growth did not occur as projected and many baseload generator construction programs continued as planned. An abundance of baseload generation became available to displace higher cost generation, which contributed to a significant increase in the long distance transfer of economy energy. Figure 2 shows how the MAAC import of economy energy has increased since the early 1970s. This change in operations has had a dramatic impact on the MAAC system and how it is operated.

EXPERIENCE

Today, the MAAC transmission system is heavily utilized to maximize delivery of economy generation from external systems and from western areas of MAAC to eastern load centers. Figure 3 shows the monthly transmission system utilization for 1983 and 1984. This measure of utilization indicates how close the system was to the most restrictive limit during each month. It should be emphasized that operating principles and standards are not exceeded.

The MAAC system is operated to single contingency limits. Both ampere loading and voltage drop conditions are used to establish these limits. Ampere loading limits are monitored by an on-line program using actual line flows and distribution factors. This security assessment method works well for ampere loading limits.

Voltage drop conditions are not easily handled. An off-line procedure is employed that uses load flow programs to establish allowable MW loading on a defined boundary or interface such that excessive voltage drops will not occur for single contingencies. This method was developed as an interim procedure to establish and monitor real-time voltage limits. It leaves much to be desired.

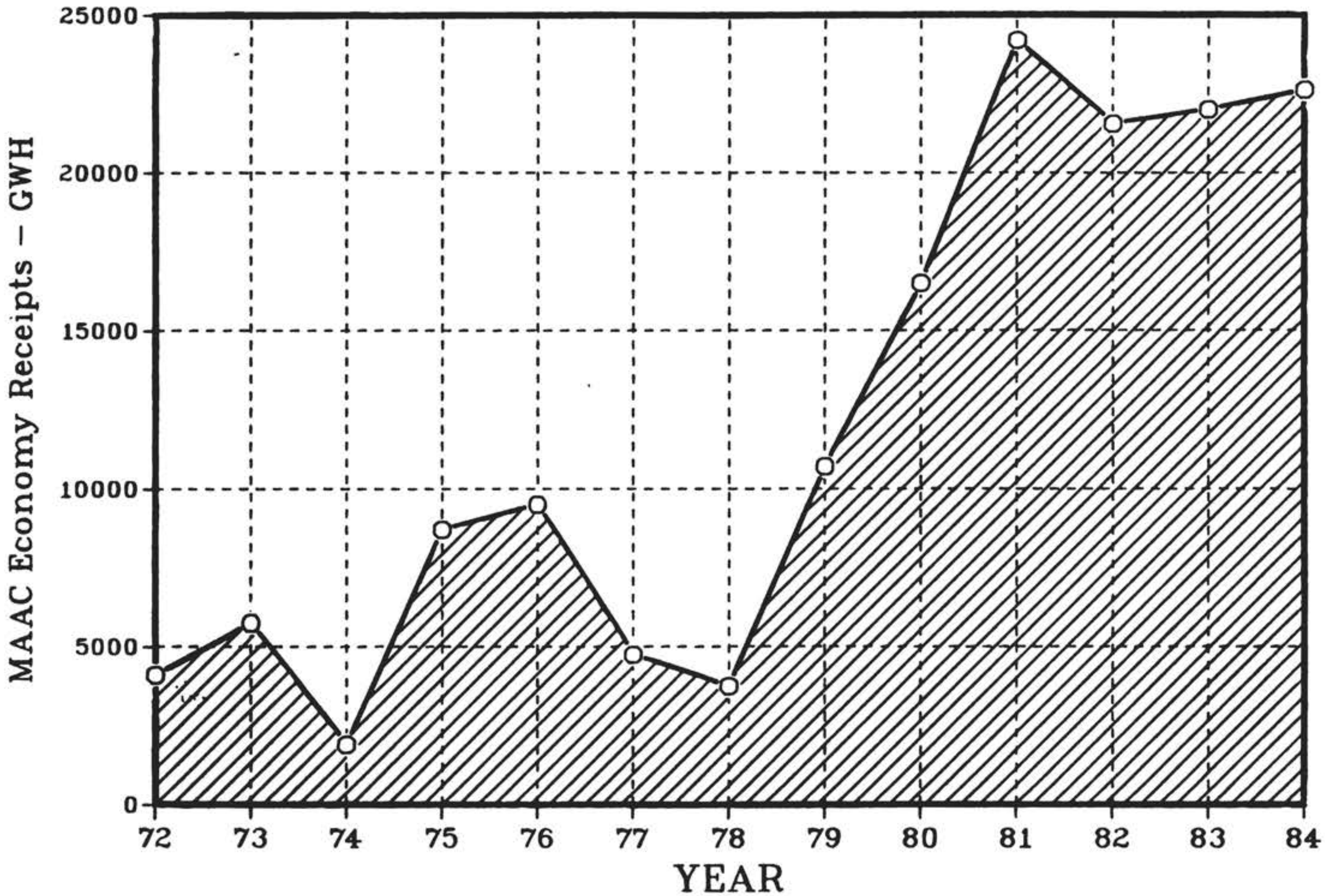

FIGURE 2 MAAC economy imports.

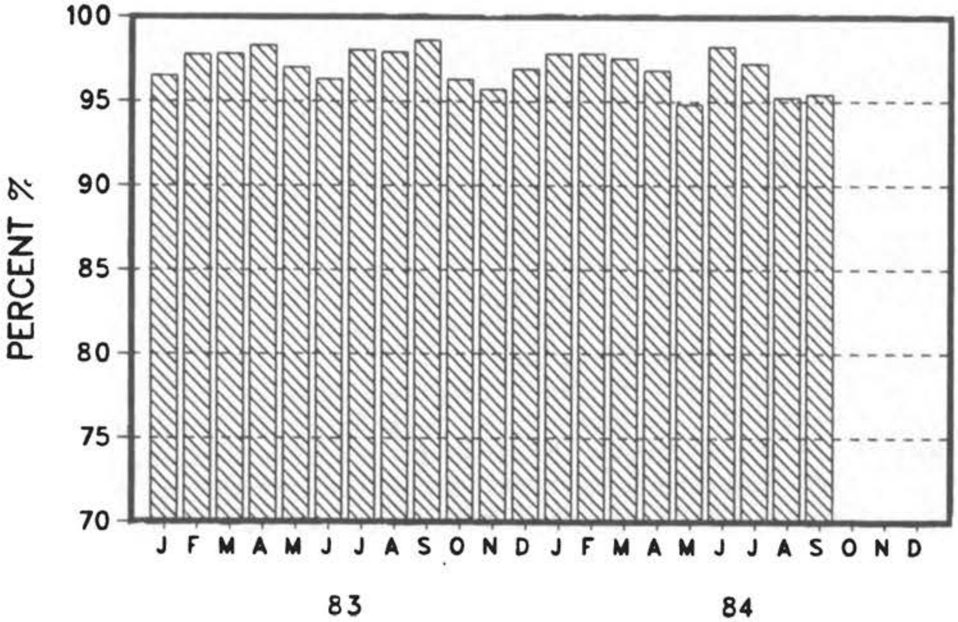

FIGURE 3 Monthly transmission utilization summary. Transmission utilization is a measure of how close the system was to the most restrictive operating limits for the month. For every hour, the contingency flows on the most limiting transmission facility at that time are compared to that facility's operating limit. That flow is converted to a percentage of the limit and is summed with the percentages for every other hour in the month. The sum total is then divided by the number of hours in the month to derive thee total transmission for the month.

Voltage limits have been the predominant limiting conditions for economy transfers in the MAAC system during the past few years. For example, during 1984, voltage limits accounted for about 85 percent of the limited operation and ampere limits accounted for the remaining 15 percent. The predominant limiting conditions are those with the least adequate method of monitoring and security assessment.

Operation and control of the bulk power electrical network has become more critical because of the higher transmission system utilization created by the west to east transfer of economic power. NERC analysis of major power system disturbances indicates that there was high utilization of the transmission system in at least one-half of the disturbances analyzed. Some of the reasons for this are as follows:

1. The system is operated within accepted operating principles and standards; however, multiple component outages that are outside the criteria do occur occasionally. Since the system is frequently close to limits, these multiple contingencies are more likely to put the system into an uncontrolled disturbance. The higher magnitude and longer duration of transfers creates more exposure to the occurrence of significant multiple contingencies.

2. Economy transfers create widespread effects that may not be recognized. Parallel flow can stress weak areas in the regional networks, which are not directly involved in the transaction. Operators may not be aware that these critical situations exist and may not be prepared to take proper corrective action if needed.

3. Importing areas become heavily dependent on transfers and may not be capable of rapid adjustment following loss of a generator or major transmission line. Generating capability (MW and MVAR) is not available quickly to readjust the transmission system. This can be caused in the near term by economic shutdown, and in the long term by retirement, mothballing, or extended maintenance outages.

4. The incentive to maximize economy transactions can lead to application of devices and shortcut methods. These complex and interrelated control and protection schemes can adversely impact system security. They can also result in heavier loading of existing facilities, which increases the exposure and consequences of multiple facility contingencies.

Continuing pressure to maximize economy transfers raises questions about the balance between economic operation and reliability. Even though the above factors indicate that economy transfers have resulted in higher risk, the criteria for reliable operation have not been changed. One approach to increase the amount of economy power delivered would be to accept lower reliability by changing the operating criteria, recognizing that some higher degree of risk may be acceptable. However, there has been little effort to move in the direction of increasing economy transactions by consciously reducing reliability. Two reasons why little has been done may be the difficulty in quantifying reliability and in defining an acceptable level of risk.

No electric power system is totally fail-safe because it is not practical to design and build such a system. When the system is in an emergency operating condition, the operators must take over through manual control or the automatic control and protection schemes must function. The purpose of these actions is to regain control and quickly return the system to safe operating conditions. If the emergency is severe, some of the system may be lost. Under these conditions the objective is to preserve as much of the system as possible.

The operator has several tools to use in the system preservation stage. Operating instructions are followed as the emergency situation develops. These instructions include procedures to follow during severe weather conditions and a series of actions to control load, such as voltage reduction, curtailment of nonessential load, and radio/TV appeals. Other actions include phase angle regulation control, adjusting generation dispatch, quick start generation, and, if necessary, manual load shedding and rotating blackouts. The objective of these actions is to maintain a balance of generation and load and to keep transmission facilities within acceptable loading limits.

There are several automatic controls and protection schemes in place to supplement manual control. A balance of load and generation is maintained by controls that automatically call upon generators to increase or decrease loading to maintain scheduled interchange between control areas. Automatic reclosing of transmission lines is an attempt to keep the transmission system intact by restoring lines to service immediately after clearing temporary faults. Some automatic reclosing is supervised by synchro-check relays. This prevents possible equipment damage and initiation of power swings, but it could also prevent the reclosing of a line when it would be desirable. The underfrequency load shedding and generator overspeed protection schemes are an attempt to balance load and generation should the system separate into electrical islands.

If part or all of the system is lost, it must be restored to normal as quickly as possible. The success of the preservation steps will determine the extent and difficulty of the restoration effort. Individual companies have developed general restoration plans for the operators to follow. The 500 kV system restoration is coordinated by the power pool interconnection office. The difficulty in planning for restoration is the fact that system conditions are unknown and can vary considerably. Some companies have conducted restoration drills for hypothetical blackout scenarios. These drills have been valuable in defining communications within the company, among the affected companies, with the power pool, and with the news media. The drills also have a technical value because they make people think through a particular situation and provide an opportunity to practice a general restoration plan.

NEEDS

Based on this summary of experience, the author has developed a list of ten "Needs" that could enhance regional energy exchanges and service continuity during normal and emergency conditions. These are based primarily on observation of MAAC experience and interactions with neighboring regions.

1. Develop and implement an improved method of security assessment for voltage limited conditions. An "on-line" system would allow transfers to be adjusted as system conditions change and would provide more accurate knowledge of how close the system is to its real limits. Such an improvement could allow an increase in economy transfers without adversely affecting reliability.

2. Develop a means to take immediate corrective action to prevent a cascading disturbance following a low-probability multiple contingency outage. This could be an automatic or computer-aided preservation measure directed to a known severe contingency such as loss of all lines at a substation or all lines on a right-of-way.

3. Enhance communication and coordination of system conditions and actions taken between regions. Examples of the information exchange are economy/emergency transactions scheduled, critical facility loadings, occurrence of significant events, scheduling critical facility maintenance outages, and managing schedules and actions that compete for use of the same facilities. Better information exchange and coordination of efforts could increase the utilization of existing facilities without lower reliability.

4. Develop quick-start generating capacity to rapidly adjust the system to safe loading levels following generator or transmission line outages. Alternatives to combustion turbines and load shedding may be such equipment as storage batteries or fuel cells. Economic transfer capability could become restricted if sufficient rapid readjustment of generation is unavailable in sufficient quantities.

5. Develop the means to balance system reliability and the economics of increased transfers. Reliability must be quantified for a large generation/transmission system that is continually changing. An acceptable level of risk must be determined, as well as a method to compare the state of the existing system to the risk standard.

6. Improve preservation measures that are not tied to specific predefined outage conditions. One suggestion for development could be computer-aided analysis capability to help the operator make decisions when faced with emergency conditions. Examples might be to determine specific system adjustments required by local severe weather conditions or to keep track of rotating load shedding. Another suggestion could be the development of schemes to preserve as much of the system as possible during a severe emergency. One example would be to monitor system voltage and initiate selective load shedding steps to avoid a widespread disturbance. The action taken should depend on existing system conditions, tend to minimize load shed, and occur prior to underfrequency load shedding. Another example would be to isolate

generation and load in equal amounts so that generating units do not have to be shut down. This would aid in restoration time since some units have very long startup times following total shutdown.

7. Develop ways to assist the operators to restore the system quickly and safely if some or all of it is lost. The assistance should provide opertors with flexibility to deal with many possible situations and practice capability by using a system simulator that closely resembles the actual system. Such a simulator could also provide training during the preservation stages.

8. Exercise extreme care in developing and applying devices and control and protection schemes. Due to the complex and interrelated nature of this equipment, improper operations could make conditions worse. Devices and control/protection schemes should not replace sound planning practices and system-justified reinforcement as needed to support system growth.

9. Develop operator training programs so that operators can keep pace with development and implementation of new control and protection schemes. Operators must know and understand the purpose of these devices and systems and how they are expected to operate. Improved simulation techniques that allow practice in real-life situations would be valuable.

10. Provide tools and procedures for the analyst to use in system studies to design and implement various new control and protection systems. These tools must be practical to use and be well documented.

FAILURE MECHANISMS IN BULK POWER SUPPLY SYSTEMS

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INTRODUCTION

Power System Reliability: The Public's Perception

The essential requirements placed upon electric utility systems are to provide customers with safe, adequate, and continuous service at reasonable cost. This places an obligation upon electric utility systems to produce, transport, and distribute electrical energy in a manner that maintains high quality of service to consumers and preserves the integrity of the interconnected system (DOE, 1981).

While these broad requirements have been in effect nearly as long as alternating current systems have existed, the absolute quantitative expression of these characteristics has evolved as public needs and expectations have changed.

Quality of service established itself as a factor in commercial competition between alternative energy supplies for illumination and power early in the history of electric utility systems. Today's requirements place high priority on service continuity and fast restoration following loss of service. As a result, the availability of service realized by electric utility systems is high. For many years, North American systems have achieved average service availability indices of 0.9997 to 0.9998. Indices for describing service performance are illustrated in Table 1.

The principal causes of sustained interruption of service to customers served by the distribution system are weather related, such as extreme winds, lightning, snow, and ice storms. Equipment-related faults, outages, and malfunctions; public interference; operations related problems; and troubles within the customer's own system are also important causes of interruption. Seventy to ninety-five percent of events resulting in sustained interruption of service to customers arise in the distribution system (IEEE Committee Report, 1975; Power Technologies, Inc., 1981).

An important fraction of bulk power disturbances resulting in interruption of service has involved the malfunction of protective relaying and supervisory control systems (Power Technologies, Inc., 1981; Billinton, et al., 1983).

TABLE 1 System Reliability Indices

BASE SYSTEM (Example)

1. Customers Served	8.3 million
2. System Peak Demand	35 GW
3. Annual Production	156 Twh

I. SUSTAINED INTERRUPTION DATA (Annual)

4. Number of Interruption Reports	77,500
5. Customer Sustained Interruptions	12.4 million
6. Customers Affected	7.5 million
7. Customer-minutes Interuption	843 million

II. REPORTABLE BULK POWER INTERRUPTIONS 100 MW OR MORE FOR 15 OR MORE MINUTES

8. Number of Bulk Power Interruptions	5
9. Sum of Interrupted Loads	1290 MW
10. Sum of Interruption Durations	200 minutes

CUSTOMER INDICES (DOE, 1981; IEEE Committee Report, 1975; Billinton, et al, 1983)

11. System Interruption Frequency Index: $\frac{(5)}{(1)}$ = 1.49/yr

12. Customer Average Interruption Duration: $\frac{(7)}{(5)}$ = 68 minutes

13. Customer Interruption Frequency Index: $\frac{(5)}{(6)}$ = 1.65/yr

14. System Annual Interruption Duration: $\frac{(7)}{(1)}$ = 102 minutes/yr

15. Average Service Unavailability: $\frac{(14)}{525600}$ = .00019

16. Average Service Availability: 1.-(15) = .99981

17. Customers Interrupted Per Event: $\frac{(5)}{(4)}$ = 160

BULK POWER INDICES (DOE, 1981; Billinton, et al., 1983)

18. Loads Interrupted Per Event: $\frac{(9)}{(8)}$ = 258 MW

19. Bulk Power Interruption Index: $\frac{(9)}{(2)}$ = .037

20. Bulk Power Interruption Duration: $\frac{(10)}{(8)}$ = 40 minutes

In general, interruption performance varies with load density and the size of load served. Low load density areas (suburban and rural) are usually supplied from radial distribution feeders. Higher load density areas may be provided, by feeders, with switching to permit sectionalizing and transfer of loads. Service to higher load density areas (commercial and urban) and to essential public services may be provided with redundant facilities, such as spot networks and secondary networks; service to major industrial loads and to large secondary networks may be from the bulk power system. As a result, the reliability of service to high density load areas, essential public services, and large commercial and industrial loads is correspondingly higher than for the lighter load density areas. Historically, the level of service reliability provided has corresponded closely to the value placed upon service continuity by the type of customer and public function. Surveys show consistently that industrial operations and commercial functions put a higher value on continuity of service.

The nature of the interruptions caused by disruptions and failure in the bulk power system differs in extent, frequency, and effect from interruptions arising in distribution systems. The number of customers interrupted per case of interruption in distribution systems is usually small, ranging from a few customers to a few hundred and averaging around 150 customers affected per interruption. Disturbances arising in the bulk power system can affect large numbers of customers and can have widespread social and economic impacts (DOE, 1981; Power Technologies, Inc., 1981). Major failures of the bulk power system have resulted in interruption of hundreds of megawatts of load and interruption of service to hundreds of thousands of customers for periods of more than a day. Public and political reaction is influenced strongly by the severity, consequential damages, and type of facilities affected.

The public has tolerated localized outages arising in the distribution system if the interval between outages is reasonably long and service restoration proceeds within a short time (less than four hours). On the other hand, public reaction to widespread interruptions has been strong, particularly if the source of disturbance cannot be identified readily with widespread and severe natural causes, such as hurricanes, widespread thunderstorms, tornados, or severe ice storms. Civil regulatory and legal actions have resulted from prolonged interruptions of service, particularly when widespread failure interferes with such public facilities as water, sewage, health, safety and protection, transportation services, and lighting. On the other hand, the public has responded to appeals for voluntary curtailment and has accepted emergency load relief measures to protect the power system, provided restoration of service is prompt (Power Technologies, Inc., 1981).

Failures

What exactly does one mean by "failure" and by "failure mechanism" in the context of the bulk power system?

The term failure is associated with the termination of the ability to perform a required function. While broadly useful in the study of bulk power systems, the term must be employed with care for failure in a system with capability margin and with distributed generation and load that may be modal in nature and of varying degree. Furthermore, the term failure may be applied in an absolute sense to the disruption of service to consumers or in a relative sense to an unsatisfactory system response to a defined test or disturbance.

The standard definition of the term failure mechanism is a physical, chemical, or other process that results in failure. It is noted that the circumstance that induces or activates the process is called the "cause of failure."

These concepts tend to focus on the idea of a single cause of failure and a single mechanism, concepts that are perhaps best applied to the description of the failure of discrete components rather than to distributed systems. Extension of these concepts is necessary to address the mechanisms of failure in the bulk power system.

To ensure that the distinction between component failures and system failures is clear, failure in a system reference is measured relative to the degree with which the system cannot serve its function to provide safe, adequate, and continuous service at reasonable cost. From the consumer's viewpoint, cessation of service would be a service failure. Events of very reduced voltage or persistent flicker would be service disruptions. The number of consumers affected would be indicative of the extent or degree of failure. The failure and outage of a component does not necessarily result in a system failure. The system margin to failure is generally influenced by component failures, but the margin is not necessarily eliminated by failure of any single component or outage of any one unit.

Categories of Failure

Many degrees of failure are possible within the power supply system. As noted, the ability of the system to provide electrical service can be diminished, depending upon the type, extent, and severity of component failures and unit outages. There are at least three broad categories of failure, including service deficiencies, emergencies in the supply system, and power system interruptions.

For example, service deficiencies include events of service voltage excursions, dips, surges, harmonics, and unbalance. Depending upon the susceptibility and vulnerability of customers, equipment, the effects of these events may range from mild annoyance to equipment damage and process interruption.

Power supply emergencies arise when demand exceeds capability. Deficiencies arise from a shortfall of resources, outage of generating capacity, or limitations in the transfer capability.

Power system interruptions cause sudden and uncontrolled interruption of service. The extent of interruptions varies widely, depending upon what facilities are affected and consequent protection, control, and operations actions.

Disturbances in the bulk power supply system can give rise to effects spanning all three categories of failure. One characteristic of disturbances in the bulk power supply system is the tendency to propagate their effects over a wide area.

RELIABILITY PRINCIPLES FOR DESIGN AND OPERATIONS

Overview

Design and operating philosophies for interconnected bulk power systems have been to provide adequate reserves to minimize the risk of power supply emergencies and to provide system strength to withstand specific classes of disturbances (DOE, 1981; Power Technologies, Inc., 1981).

The North American Electric Reliability Council has adopted the following definitions to describe reliability attributes for bulk power systems (North American Electric Reliability Council, 1985):

- o Reliability, in a bulk power electric system, is the degree to which the performance of the elements of that system results in power being delivered to consumers within accepted standards and in the amount desired. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on consumer service.
- o Bulk power electric system reliability can be addressed by considering two basic and functional aspects of the bulk power system--adequacy and security.
- o Adequacy is the ability of bulk power electric systems to supply the aggregate electric power and energy requirements of the consumers at all times, taking into account scheduled and unscheduled outages of system components.
- o Security is the ability of the bulk power electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components.

Adequacy relates to the provision of sufficient generation and transmission capability to satisfy customer load demand in the presence of scheduled and unscheduled outages of generation, transmission, and distribution facilities. Adequacy is assessed on both deterministic (contingency) grounds and risk balance in terms of static generating capacity reserves and transmission and distribution load carrying capability.

Security relates to system capability to withstand disturbances arising within that system. Design and operating philosophies have included generic performance tests (umbrella tests) that will ensure that the system has the capability and flexibility to maintain secure operation and bulk power system integrity.

Good system design practice requires the application of testing procedures to establish margins to failure. Margins can be measured in adequacy terms, such as load carrying or transfer capability, and in security terms, such as critical clearing times and insensitivity to protective relaying and control malfunctions.

Design and Operations Reliability Objectives

This section focuses on the impact of system design and operation on power system reliability. A design philosophy has evolved for the bulk power system that ensures that the system will have the capability and flexibility to:

- o supply aggregate electric power and energy requirements of the consumers at all times;
- o maintain secure operation;
- o maintain bulk power system integrity;
- o limit the extent of bulk power system failure and thus limit the extent of widespread interruptions; and
- o achieve rapid restoration of shutdown bulk power systems and thus limit the duration of widespread interruption.

There is a very close relationship between the continuous operation of the bulk power supply system and continuity of commercial and industrial activity. Interruption of operation of even portions of the bulk power supply system can have adverse effects on commercial and industrial activity and may seriously jeopardize public safety.

However, the possibility of shutting down significant portions of the bulk power supply system must be considered in any public policy and public contingency plans. This possibility must be addressed with procedures similar those used for contingency plans that are prepared to respond to widespread natural disasters. The possibility of bulk power supply system loss as part of a widespread natural disaster must be anticipated.

Considering the adverse economic impacts and risks to public safety that can result from interruption of the operation of major portions of the bulk power supply system, it is necessary to establish an objective; the bulk power supply system must be designed, constructed, and operated such that reasonably foreseeable contingencies will not result in the loss of a major portion of the system. Due allowance must be made for maintenance of system components as a part of the preconditions for the assessment of reasonably foreseeable contingencies. Consideration must be given to the power transfer duties that will be imposed the bulk power supply system by power flows arising from the normal economic dispatch of generation. And contingency conditions must reflect line configurations (double circuit construction, common right-of-way), contamination considerations, and extreme weather hazards of high wind gust forces, ice and snow loading, and flooding.

The bulk power system should be designed and operated to minimize risk of the propagation of adverse effects of major disturbances that exceed system design criteria. It is inevitable that, in time, criteria based upon reasonably foreseeable contingencies will be exceeded by such events as major natural disasters and catastrophic accidents. The objective sought is that the bulk power system should be designed with sufficient protection and operated with sufficient reserve to confine the extent of the disturbance and defend against the propagation of interruption beyond the portion suffering the disaster.

The means for reconfiguration and restoration of operation of the bulk power supply system should be sufficient to permit rapid recovery from interruption. The expected time for restoration of bulk power transmission facilities and service to essential public services should be no more than four hours. Communications, control, and switching centers should be provided with emergency onsite auxiliary power capability to permit independent monitoring and operations capabilities for rapid reconfiguration and reenergization.

Reliability Criteria

A hierarchy of procedures and criteria are employed in the design of the bulk power system to address the need to maintain acceptable service reliability. These criteria may frequently appear to address different issues at the levels of the company, pool, and region.

For example, company-level transmission and subtransmission reliability criteria usually address acceptable voltage levels and allowable excursions under normal and emergency conditions. Company criteria address substation security classes with regard to capabilities under specified levels of loss of in-feed and transformer contingencies. Company criteria also set service restoration time objectives for specified events to define spares requirements and locations. Company criteria address component loading-time limits for normal and emergency operations.

Operating reserve and transfer capability objectives are coordinated at the pool level. Transfer capability objectives must be defined to exploit opportunities to share capacity reserves and use load diversity, as well as gain the benefits of sharing resource diversity. System capability is assessed in terms of acceptable responses to classes of more probable faults and outages under specified initial conditions. These include normal transfers resulting from scheduled interchanges and economic dispatch. They also include the emergency transfers resulting from generation shortfall and transmission outages.

The discussion so far has been concerned with static and dynamic assessment of the bulk power system under the disturbances caused by classes of more probable contingencies. The primary emphasis is on maintenance of service and preservation of interconnected system operation. Faulty facilities may be removed from service and units directly affected by the fault may be tripped, but system stability is to be preserved and component loadings must be within acceptable ranges such that system readjustment may restore loadings to within long-term capabilities.

Since the 1965 and 1968 disturbances, attention to the hazards of disturbances that may lead to widespread impact has been the focus of regional groupings of utilities and pools. The formation of the regional councils were a direct consequence of the 1965 and 1968 widespread failures of the bulk power supply. Accordingly, the priorities of the Regional Councils have been focused on the capability to minimize risk of propagating the effects of bulk power system disturbances from a disturbed area to its interconnected neighbors. These disturbance performance tests are concerned with system withstand characteristics under "maximum credible disturbances"--that is, the "possible but improbable" class of events. The admissible responses are concerned with the means to confine the area of severe impact to prevent propagation of uncontrolled outages and separation of the network in areas adjacent to the system being subjected to test.

Thus, it should be clear that there are a hierarchy of criteria addressing reliability aspects of transmission and subtransmission performance and bulk power performance under normal, emergency, and "possible but improbable" conditions. Certain of these criteria may be evaluated using such static tools as alternating current load flow programs and simplified linearized power flow models. Failure may be judged in terms of satisfactory response in a static sense to the outage of specified units under specified terms of interchanges and dispatch. This is a "design" failure measure and does not necessarily relate to actual system failures as defined for deficiencies, emergencies, and interruptions.

Prediction of the interruptions caused by disturbances arising in the bulk power supply system must of necessity be done with models capable of representing dynamicl responses to sequences of faults and operations, protection, and control disturbances. These simulations must include the short-term energy storage (boiler) characteristics, as well as the electromechanical energy balances of the electrical system and prime movers. Full representation for typical system problems of pool or regional size is possible in contemporary simulation programs for specific or "defined" preconditions and contingencies. However, the prediction of the ways in which a bulk power system could fail, a necessary task in the prediction of bulk power system reliability, would be a difficult indeed (Power Technologies, Inc., 1981; Billinton, et al., 1983; CIGRE Study Committee, 1980).

Characteristic Patterns of Widespread Disturbances

The profile of a widespread interruption of service typically includes two or more of the following initiating and consequential causes:

- o heavily stressed system,
- o critical facilities on maintenance,
- o high hazard conditions causing multiple failures,
- o protection or control system failure or malfunction, or.
- o operations error.

It is possible to identify characteristic patterns in the development of many of the widespread interruptions. This is illustrated in block form in Figure 1. A sequence of events leads to a significant imbalance between demand and generation in all or significant parts of the system. The system or its islanded parts stabilize (at points S1 or S2 in the Figure) through prime mover governor action and automatic generation control, load shedding, or load disconnection, and through generator tripping--all actions intended to eliminate the imbalance between demand and generation and to restore the frequency in each island to the nominal value. However, if these control actions are not sufficiently matched to the imbalance, further adjustments of generation are called for. If these are outside the capability of the units, further disconnection of demand or loss of generation occurs. Three possible cases, all of which have occurred in practice, are shown in Figure 1.

Essentially, the containment of a major disturbance requires that the events shown in Figure 1 be halted as early in the sequence as possible. The ideal way to achieve this is to match the controlling actions as closely as possible to the magnitude of the disturbance so that further changes to system operating conditions are minimized. The time scale of the events will frequently be so short that the control actions need to be automatic.

Restoration Issues

Restoration from the shutdown state has generally followed the pattern shown in Figure 2. Stops include identifying the problem and ascertaining the readiness of deenergized transmission and station components, and beginning the reenergization of blacked-out portions from available sources. Communications, monitoring capability, and onsite auxiliary power capability are key elements in speeding reconfiguration and in staging reenergization. Control of voltage and balancing load pickup with on-line capability are essential factors in the achievement of restoration. Restoration of demand is a necessary part of the reenergization procedure to load transmission and generation to effect control of voltage. Prompt restoration of external ties is also helpful in that it provides an external reserve to help cover short term deficits and surpluses of real and reactive power as generation and demand are reconnected. It also assists in stabilizing frequency and voltage conditions in the affected area. A basic requirement is the presentation to system operators of the state of the system when it has attained a steady though depleted condition and, most importantly, a knowledge of the causes of the disturbance and the status of the

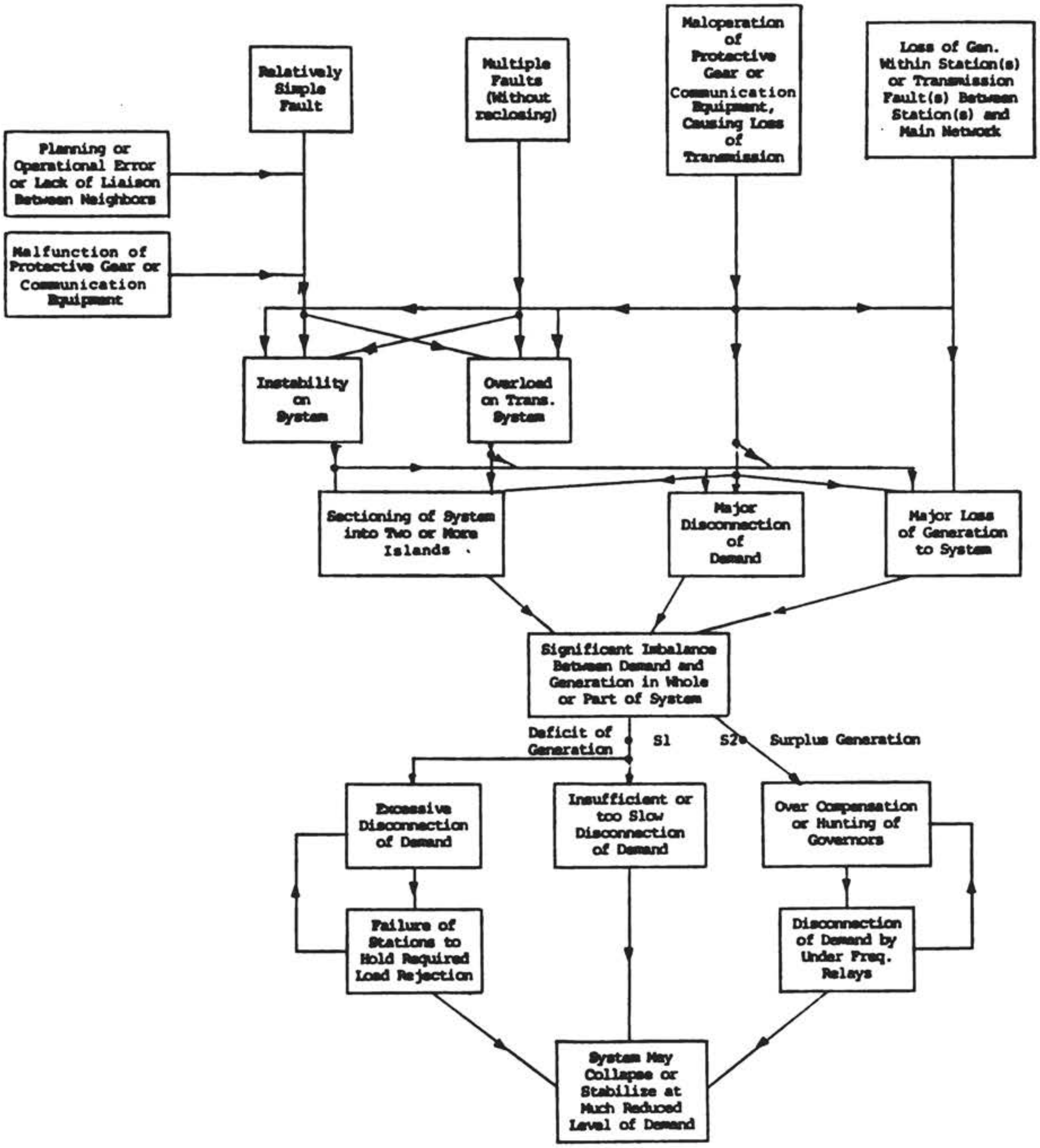

FIGURE 1 Typical measurement of large scale or widespread system disturbance.
Source: Power Technologies, Inc.

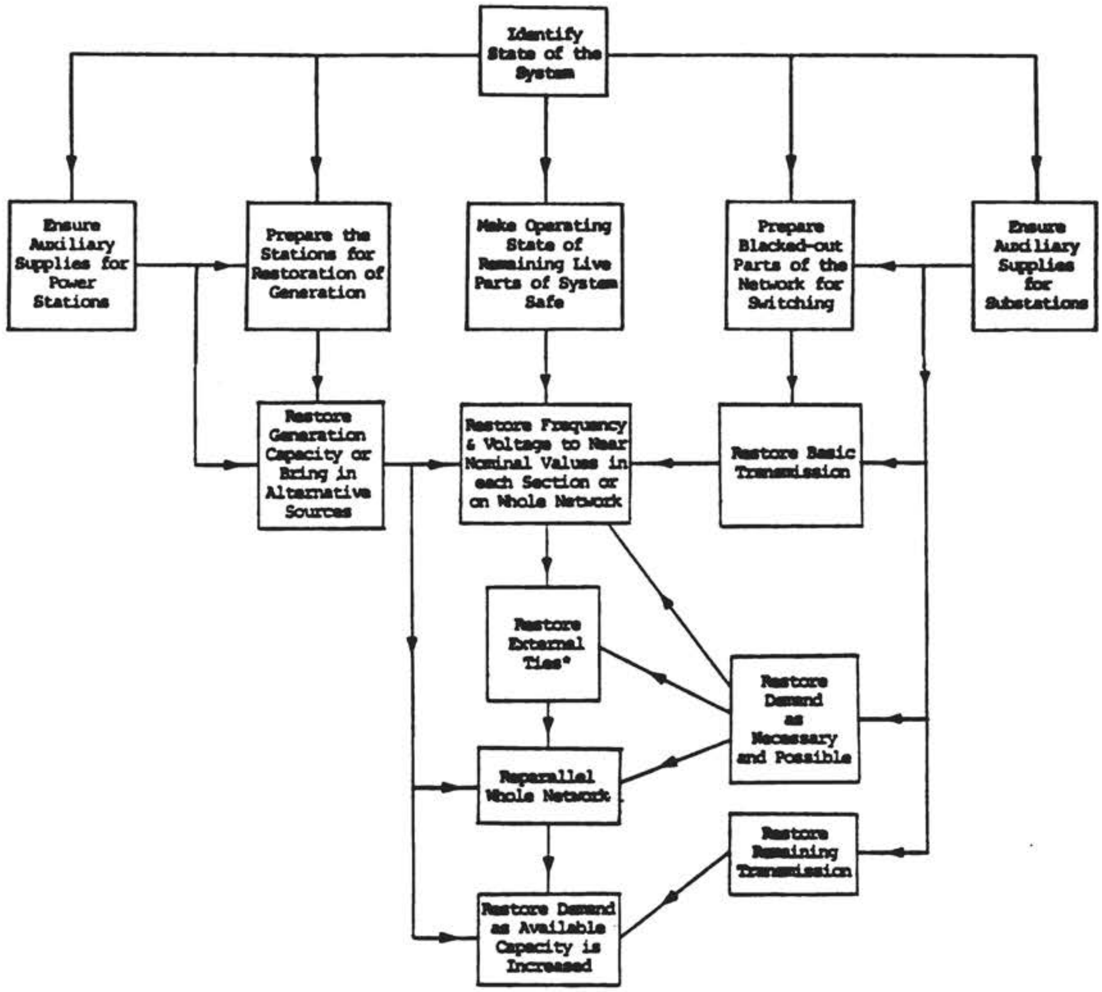

FIGURE 2 Typical sequence of restoration.
Source: Power Technologies, Inc.

bulk power system units and components. Secure communications and auxiliary supplies for control rooms are essential to the coordination of the restoration process. Adequate, secure power supplies for cable pressurizing, bus section, transformer, and circuit switching operations, as well as supervisory control for switching and tap changing, are essential to the restoration process.

MODELING ISSUES

Surveys of major disturbances suggest that only one in three of these events has been caused by what might be called an abnormal fault condition, that is, something exceeding the defined contingency criteria governing the systems design and operation. About half of the faults classified as abnormal have been caused by bus faults or breaker failures. Fully one-third (to 40 percent) of the events were aggravated by the malfunction of protection or control. This distribution of causes is not surprising in that malfunctioning equipment or deficient operational planning provisions for example could represent a contingency hazard that, on the occurrence of more probable faults or contingencies, would precipitate a multiple outage of bulk power system units.

Present-day modeling capabilities can handle system stress, maintenance, and high hazard causes, but malfunctions and errors are not reasonably modeled or predicted at present. Instead, use is made of "umbrella" type disturbance tests. Research is warranted into the mitigation and the modeling of malfunctions and errors.

Simulation programs are available to meet the requirements for performing adequacy evaluations for composite generation and transmission systems, to represent normal and emergency requirements on the transmission network, and to determine useful design indices with which reliability evaluations may be made. These tools must be of static form for the near term, owing to limitations in modeling and computing capabilities, to study and enumerate properly sufficient events in a pool or regional system model and to properly represent the effects of control and protection systems and operations strategies and errors.

SYSTEM FAILURE MECHANISMS

Though one might list a spectrum of mechanisms by which large scale systems may fail, six deserve individual note in that the roles that they have played in widespread disturbances and wide spread interruptions have been significant.

These mechanisms include deficits in operating capability; extreme loading of lines and/or transformers, resulting in uncontrolled separation and islanding; local reactive deficits resulting in voltage collapse; disturbances resulting in instability; widespread storms; and associated outages. Each represents a distinct form of failure and requires different control actions to mitigate the hazard of bulk power system failure.

Operating Capability Deficits

This mechanism may apply to an isolated area and even applies to the eastern interconnection of North America. Examples include the 1977 New York City shutdown, the September 1970 eastern seaboard capability deficit, the 1977 Tennessee Valley coal freeze-up, and the 1978 coal strike. In all but the first incident cited, mitigative or defensive measures to control the deficit were successful.

Operating reserve rules are intended to ensure that the system is able to replace any lost generation or transfers from spinning or quick-start units. Typically, these criteria require specified load pickup capability to be in on-line generation and the complement to be in quick-start generation. For interconnected systems the load pickup time limit may be five to ten minutes, an interval related to the short-term emergency limits. Evaluation of the adequacy of operating reserves in the early stages of a system upset requires consideration of governor response and automatic generation control action. This is because frequency excursions as detected by governors and interchange excursions as perceived by automatic generation control will be the earliest signals of a system emergency involving transfer capability or generating capacity loss. The effectiveness of operating reserve criteria involving generation reserves, underfrequency load shedding, and automatic generation control depends upon the transient response of the plant over periods ranging from several seconds to many minutes. Adequate transient responses of governors, underfrequency load shedding relays, and generator startup controls in the seconds to minutes following generation loss, line loss, and separation are key factors in the prevention of island collapse and the confinement of the disturbance. In the case of operating capacity deficits, areawide reductions of load are effective in mitigating the effect of the shortfall.

Voltage Collapse

Voltage collapse is a phenomenon associated with local shortages of reactive capability. The onset of the voltage collapse phenomenon is illustrated by the case of a highly stressed transmission system feeding a heavy load radially through temporarily weakened transmissions and with minimal or no synchronous or SVC capability in the load area. Through successive contingencies, a point can be reached at which a load of constant real and reactive demand cannot be supported. In this instance, a threshold is reached beyond which a very small increment of load will result in a disproportionately large drop in receiving bus voltage. The effect of voltage control by TCUL transformers in the load area is a key factor in aggravating the impact of collapse. Subtransmission and distribution systems include TCUL transformers and regulators to hold the consumer service voltages as nearly constant as possible. As long as the controls can perform their intended functions, customer demands will be met despite any changes in loading and reactive loss conditions on the transmission system. Anomalous behavior results; efforts to raise distribution system voltages by tap change or by capacitor switching in the distribution system can aggravate the problems in the transmission system and result in very low voltages at transmission buses (Undrill, 1983). The phenomenon of voltage collapse and the threshold are influenced by the voltage characteristics of the loads in the distribution system (Undrill, 1983; Clark et al., 1970). System operators must have the background and monitoring capabilities to recognize voltage problems indicative of voltage collapse. In particular, appropriate remedial actions that must be taken include load reduction in the problem area. Attempts to raise voltage by the addition of shunt capacitors in the receiving areas of the transmission system must recognize the essential limitations of the static capacitors as sources of reactive power to support voltage at the receiving end of the transmission system. Reactive power provided by shunt capacitors varies as the square of the bus voltage; that is, reactive support becomes diminished under the very conditions leading to the need for increased support. The capabilities of controllable sources of reactive power, including synchronous condensers and controllable static var devices, can provide such support for receiving buses of transmission systems. Of course, the means to reduce the series or to transfer impedance of long lines through the use of series capacitors provides a direct and effective way to extend power transfer capability.

With the sustained attention and interest in long distance transport of low-cost energy to load areas, and with the continuing difficulties in obtaining approvals for new rights of way for transmission lines, it is clear that the issue of voltage control of receiving systems will remain an issue of significance.

Overload Cascading

The third failure mechanism to be discussed is the phenomenon of automatic or emergency manual removal of transmission units due to overload. This mechanism was celebrated in the November 1965 blackout of the Northeast. Loading on four parallel transmission lines reached protective relay trip levels and tripped sequentially during an attempt to reduce their loadings by tap change on a phase shifting transformer in a parallel path. The uncontrolled separation of New York City from the eastern interconnection in July 1977 involved emergency manual trips of circuits and equipment failure after the loss of the northern in-feeds. Severe lightning activity, protective relay and reclosing malfunctions, failure of local generation to start and load, and insufficient load shedding in the New York area led to the shutdown. Mitigation of the hazards of overload cascading and uncontrolled separation involves identification of the problem areas and of the transfers causing the problem. Underfrequency load shedding is of minor help in responding to the hazards of overload cascading before system separation and islanding take place.

Instability

The phenomenon of rotor angles falling out of step is a long and well-recognized mechanism of system failure. Without exception, regional, pool, and company design and operating criteria recognize and endeavor to avoid this failure mechanism. Instability has occurred in systems weakened by the outage of transmission facilities, which are then subjected to severe faults or to combinations of faults and breaker or protection malfunctions. The blackout in San Diego in March 1978 was the result of a three-phase bus fault and the failure of protective relaying to clear the faulted station. A maintenance error resulted in system instability, separation, and shutdown of the resulting island. Generators have lost synchronism under conditions of underexcitation resulting from high voltage on lightly loaded cable systems following isolation and underfrequency load shedding. Generators have pulled out of step under weakened transmission system strength due to extensive but dispersed loss of transmission facilities. In the specific instances, loss of synchronism was the result of growing oscillations of rotor angles--that is, a system condition resulting in negative damping or "dynamic instability."

Widespread Storms

These are the severe storms that cover wide areas and cause loadings on overhead facilities in excess of withstand. The risk of loss of many facilities and consequent widespread interruption of service during major storm disasters is high--in fact, by definition, certain. Risk-based structural design is under development and application. Disciplines for measuring benefits and the social costs of interruptions are not well developed, and data are insufficient to permit trade-off studies of changes in criteria or philosophy.

A companion issue in need of attention concerns the prediction of the risk of loss of facilities on common structures and common right-of-way. Studies have been reported from CEGB on the prediction of risks to nuclear stations of common right-of-way loss for in-feeds (Argent and Manning, 1985). Clearly, the subject is open for further investigation.

Another issue in need of study concerns the risk models and prediction of return periods of extremes for structure and conductor loading.

Associated Outages

Significant interruption events have resulted from multiple outage of facilities or units due to protection or control malfunction. In some instances these have been associated with maintenance and operations errors. While one may be inclined to designate these phenomena as causes, the reason for placing them in the category of failure mechanisms arises from the possibilities of isolation of significant portions of bulk power systems by protection or control malfunction. Such disturbances may or may not lead to further and more widespread interruption, but the impact is sufficient to result in significant disturbances and interruptions. It is of interest to note the number of major disturbances in the bulk power supply system that have been precipitated and aggravated by malfunctions and errors.

RESEARCH OPPORTUNITIES

If one were to form a list of the areas in the field that offer research opportunities, such a list might include the following:

o Benefits of bulk power transmission--Frequently, questions raised in siting approvals for bulk power transmission facilities or right-of-way relate to the social benefits of such facilities. Specifically, what are the improvements in system reliability to be achieved with the addition in contrast to not building the line and other alternatives? What are the costs to be assigned to widespread interruptions? How may one go about predicting the risks of widespread interruptions? What are the values to be assigned to transfer capability, taking into consideration reserves and load diversity benefits, economy energy exchanges, and resources exchanges in strategic emergencies? Clearly, present economic and reliability disciplines are not equal to this task.

o Environmental and biological risks of transmission--What are the thresholds of risks of electromagnetic fields associated with the transmission of electrical energy? What data are needed to be able to establish voluntary standards concerning acceptable EM field strengths in the vicinity of transmission lines. The issue of field effects appears to be in contention at this time. There is need for review of ongoing epidemiological studies and to review present research on the effects of EM fields--by unbiased third parties. This would appear to be a proper role of federally funded studies.

o Exploitation of resource diversity--Perhaps the most significant role served by the bulk power system, apart from the accommodation of large central stations separated from the load centers, is to provide the instrument for exploiting a diversity of dispersed resources. There is considerable flexibility and strategic capability that is realized through the bulk electric power system. Strong, reliable bulk electric power systems have provided the means to utilize a wide range of resources that are widely distributed. Opportunities exist for increasing the power transfer capability of existing facilities and rights-of-way. Opportunities exist to mitigate the environmental impact and minimize land or space use to penetrate dense load areas. And opportunities exist to review the philosophy of continent-wide synchronous systems. Would asynchronous interconnection of regions or pools be cost and reliability effective?

o Incremental cost benefit evaluations--Given the key role that protection and control systems have been assigned in bulk power systems, a reasonable question to raise concerns the allocation of capital between the primary facility--that is, the stations and lines--and the protective subsystems. Would funds applied to improve the security and dependability of protection and control subsystems and the associated communication systems buy more system security and integrity than, say, funds applied to reduce the risks of line failure due to lightning, fault clearing, or switching surge? In like manner, would greater benefit accrue if funds were applied to systems for speed switching, communication, and control capabilities to speed reconfiguration, reenergization, and restoration than for to reducing the risk of failures in the bulk electric power supply system?

o Functioning with uncertainty--Some of the greatest shocks to the electric power industry have involved profound errors on the part of management, regulatory groups, suppliers, and constructors, as well as the planners, designers, and operators of power supply systems. Forecasts of capital costs, growth of loads, fuels, costs and construction costs have all been seriously in error. While planning disciplines have been modified to respond to the uncertainties of load forecasts, the industry reaction has been a sharp swing to retrenchment and project cancellations. No doubt this action is good, although too late in some notable instances. However, there is still an opportunity to undertake research into the best approaches to planning and financing the electric utility industry in this "age of uncertainty." The Electric Power Research Institute (EPRI) is looking into this issue, but supportive basic research on the economic, resource, financial, and regulatory institutions may be worthwhile to supplement the EPRI efforts.

SUMMARY

The major mechanisms of failure in bulk power systems may be disclosed by investigations of disturbances, emergencies, and, lastly, interruptions in bulk power systems. Four distinct groupings of mechanisms can be recognized, relating to the prominent physical, extreme environmental, and operational causes, and to the less prominent institutional causes.

The performance of bulk power systems is shaped by industry, commerce, and the public through economic and political actions. Justification of new facilities to maintain past levels of performance has become an important contemporary issue. The consequences of working with the results of former and flawed decisions involving serious technological and financial uncertainties are now upon utility managements. These may have the greatest impact on shaping reliability performance of the system of the future.

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GROUP 3

ELECTROMAGNETIC FIELDS

PHYSICAL PROPERTIES OF HIGH-VOLTAGE ELF ELECTROMAGNETIC FIELDS AND THEIR INTERACTION WITH LIVING SYSTEMS

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INTRODUCTION

During the last two decades an increasing level of concern has been voiced in regard to the environmental impact and health effects of high voltage electrical systems. The interest of both the general public and the scientific community in these issues was greatly increased during the 1970's as a consequence of the environmental assessments resulting from the Navy's proposal to develop a submarine communication system transmitting extremely-low-frequency (ELF) electromagnetic fields (Hastings et al., 1977), and the hearings conducted by the New York Public Service Commission on the environmental compatibility and public need for a 60-Hz, 765-kV transmission line in upstate New York (Scott-Walton et al., 1979). As demonstrated by these environmental assessments, the range of potential biological effects from ELF fields is broad, and varies from direct physical phenomena such as contact currents to reports of subtle behavioral and physiological changes in animals and plants exposed to external fields. The study of these factors under controlled laboratory conditions has received increased financial support during the last decade from the Department of Energy, the U.S. Navy, the Electric Power Research Institute, and several public utilities. As a result, there has been a substantial increase in the extent to which the effects of ELF fields on living systems is understood (Graves et al., 1985 a,b).

The principal objective of this report is to describe the physical interaction of high-voltage ELF fields with living organisms, and especially human subjects. The emphasis will be placed on fields from 60-Hz transmission lines operating at high voltage, although many of the physical principles underlying the interaction of these fields with living systems pertain as well to other sources of high-intensity electric fields. The discussion of electromagnetic fields will also be limited to ELF fields and will not specifically consider static fields from high-voltage DC transmission lines or other sources.

HIGH-VOLTAGE TRANSMISSION LINE FIELDS

The transmission of 60-Hz electric power over long distances is generally accomplished through overhead transmission lines operating at high voltages on polyphase conductors. The associated 60-Hz electric and magnetic fields in the environment of these lines depend upon several parameters, including the line voltage, load current, phase spacing and line height (Zaborsky and Rittenhouse, 1954; Farr, 1980; Pansini, 1983). The maximum fields at one meter above ground level for line voltages of 345, 500 and 765 kV are shown in Table 1 (adapted from IEEE, 1984). Within a few meters of the centerline, the fields in air at ground level are reasonably uniform. Beyond the outer conductors, both the electric and magnetic fields decrease rapidly as a function of lateral distance and reach levels at the edge of the right-of-way that are typically less than 20 percent of the maximum values. Using the fundamental equations of electromagnetism, the spatial variation of fields associated with high voltage transmission lines can be predicted with reasonable accuracy (Deno, 1976; Tell et al., 1977; Graves et al., 1985b). However, a fundamental limitation on the ability to calculate the ambient electric field is imposed by shielding from vegetation, large buildings, vehicles and other objects within the vicinity of a transmission line.

The 60-Hz electric fields that exist within the right-of-way under a high-voltage transmission line (typically 45 to 75 meters in width for line voltages of 345 to 765 kV) are one to three orders of magnitude greater than the fields usually encountered in the household environment. Although fields up to 0.25 kV/m may exist in the vicinity of small motors or electric blankets, the electric field levels from household appliances at a distance of 30 cm are typically 30 to 60 V/m (Sheppard and Eisenbud, 1977). The average electric fields within dwellings and away from appliances are generally in the range of 1 to 20 V/m (IIT, 1984; Deno, 1984; Graves et al., 1985b).

In contrast to power-frequency electric fields, the commonly encountered 60-Hz magnetic fields in the household and work environment can significantly exceed the field levels under transmission lines. Numerous rotatory devices such as hair dryers, electric shavers, mixers, circular saws, etc., produce local 60-Hz fields (within a few cm) that exceed 1 Gauss (Gauger, 1984). These fields, however, decrease rapidly as a function of distance and the average magnetic flux density at locations away from appliances within representative homes and businesses has been reported to fall in the range of 0.07 to 8 milligauss (Deno, 1984; IIT, 1984; Graves et al., 1985b).

INTERACTION OF POWER-FREQUENCY ELECTRIC FIELDS WITH MAN AND OTHER LIVING ORGANISMS

There are several important aspects of the interaction of ELF electric fields with living objects, including the perturbation of the field in

TABLE 1 60-Hz Electric and Magnetic Fields from High-Voltage Transmission Lines

Operating Characteristics and Fields	Line Voltage		
	345 kV	500 kV	765 kV
Load current (kA)	1.0	1.5	2.0
Conductor spacing (m)	7.3	10.4	13.7
Line height (m)	9.8	10.7	12.2
Maximum electric field (kV/m) at one meter above ground	5.3	8.8	12.9
Maximum magnetic field (G) at one meter above ground	0.194	0.279	0.330

the vicinity of an object (field enhancement effects), the induced surface charge, the induced internal electric field, contact currents and spark discharges. Each of these topics will be considered here, with emphasis being placed on describing the general physical features of the electric field interaction using simple concepts derived from electromagnetic field equations.

Quasi-Static Approximation

The radiating properties of power-frequency electromagnetic fields can be neglected. In analyzing their interaction with humans or other living objects, the fields can therefore be treated as originating from static sources. This simplification, which is known as the "quasi-static approximation," results from two factors (Kaune and Gillis, 1981): (1) the wavelength of a 60-Hz field in a medium with the electrical properties of tissue is approximately 5000 m, which is much greater than the largest dimension of the body; (2) the skin depth, which is the distance from the body surface where the induced current density is reduced to 37 percent of its value at the surface, is greater than 50 m in living tissues. This distance is also much greater than the largest dimension of the body.

As a consequence of the quasi-static approximation, the electric and magnetic field components of a 60-Hz electromagnetic field behave as though they were uncoupled in their interaction with body tissues. The electric and magnetic fields can therefore be treated separately in a theoretical analysis of the interaction of power-frequency electromagnetic fields with living objects.

The External Electric Field in the Proximity of a Living Object

The electrical conductivity of air is extremely small, $\sim 10^{-14}$ S/m, and air can therefore be treated as an insulator. In contrast, the conductivity of living tissues is in the range 0.02 to 1.5 S/m (Schwan, 1957, 1963; Schwan and Kay, 1956, 1957). A human within the electric field of a high-voltage transmission line thus behaves as a conducting object within an insulating medium. The presence of a man or other conducting objects significantly perturbs the local electric field, and this effect is most pronounced on portions of the body with small radii of curvature, such as the head or a raised hand. By treating the head as a sphere of radius R with a uniform capacitance and surface charge (Deno, 1977), it can be shown from electrostatic equations that the local electric field at the top of the head, E_o, is greater than the unperturbed field, E_∞, at a distance from the head. For a man of height, h, the approximate relation between E_o and E_∞ is given by the equation:

$$E_o \simeq E_\infty (h/R) \qquad (1)$$

Using the representative values h = 1.7 m and R = 0.08 m for an adult man, it is predicted from equation (1) that $E_o \simeq 21\, E_\infty$. Significant field enhancement thus occurs near the human head.

Induced Surface Charge Density on Living Objects

The induced surface charge density, σ, at the body/air boundary is given by the equation:

$$\sigma = \varepsilon_o \hat{n}\cdot\vec{E}_o - \varepsilon_i \hat{n}\cdot\vec{E}_i \qquad (2)$$

where $\vec{E}_o$ and $\vec{E}_i$ are, respectively, the electric field intensities immediately outside and inside the body surface, $\hat{n}$ is a unit vector normal to the surface, and ε_o and ε_i are, respectively, the electric permittivities of air (8.85×10^{-12}F/m) and the body tissue. This expression for the surface charge can be simplified based on a consideration of the equation for charge conservation at the body/air boundary (Kaune and Gillis, 1981):

$$(\Lambda_o + j\omega\varepsilon_o)\hat{n}\cdot\vec{E}_o = (\Lambda_i + j\omega\varepsilon_i)\hat{n}\cdot\vec{E}_i \qquad (3)$$

where Λ_o and Λ_i are, respectively, the electrical conductivity of air and body tissue, ω is the angular field frequency ($= 2\pi f$), and $j = \sqrt{-1}$. The first and second terms on each side of the equation represent, respectively, the conduction and displacement (capacitative) currents. In air $\Lambda_o \simeq (3 \times 10^{-6})\omega\varepsilon_o$ and the conduction current can be neglected. For body tissues and fluids, Λ_i ranges from 0.02 to 1.5 S/m and the electrical permittivity is extremely large, $\gtrsim 10^5\ \varepsilon_o$ (Schwan, 1957, 1963) at ELF frequencies. For a 60-Hz field, $\Lambda_i \gtrsim 600\omega\varepsilon_i$ and the conduction currently greatly exceeds the displacement current. Equation (3) can then be approximated as

$$j\omega\varepsilon_o \hat{n}\cdot\vec{E}_o \simeq \Lambda_i \hat{n}\cdot\vec{E}_i \qquad (4)$$

Combining equations (2) and (4) gives the final simple expression for the induced surface charge density:

$$\sigma = \varepsilon_o\ (1 - j\omega\varepsilon_i/\Lambda_i)\hat{n}\cdot\vec{E}_o \simeq \varepsilon_o \hat{n}\cdot\vec{E}_o \qquad (5)$$

The induced surface charge density is therefore dependent only on the normal component of the external electric field at the body surface, and is independent of the conductivity of the body tissues.

The surface charge acquired on the skin and body hair can lead to the perception of strong electric fields by humans and other forms of animal life. The surface charges induced by the field exert oscillatory forces which lead to hair vibration and a tingling sensation. Several laboratory and field tests have been carried out to determine the threshold electric field intensity perceived by humans (Kouwenhoven, 1966; Deno and Zaffanella, 1975; IEEE, 1978; Graham et al., 1984). These studies indicate that there is considerable variability in the threshold for perception of high-voltage electric fields, with some indication that women may be less sensitive than men, possibly because of hair length. A small fraction of individuals ($<$ 5 percent) can perceive fields as low as 2 to 4 kV/m. The field levels at which 50 percent of the test subjects reported a sensation on the skin or hair were generally in the range 10 to 20 kV/m. In one study, the 50 percent perception level was lowered to about 7 kV/m when the subjects raised their hands (IEEE, 1978). This reduced threshold is a result of the field enhancement effect described above.

Short-Circuit Current to Ground in Living Objects Exposed to High-Voltage Electric Fields

The current passing from a grounded animal to earth is defined as the "short circuit" current, I_{sc}. Denoting the total induced surface charge by Q_s, then I_{sc} can be related to the average electric field at the body surface, E_o^{av}, and the total surface area, A, by the following equation which uses the approximation given in equation (5) above:

$$\begin{aligned} I_{sc} &= |dQ_s/dt| = \omega|Q_s| = \omega\iint\sigma dS \\ &\simeq \omega\varepsilon_o\iint\hat{n}\cdot\vec{E}_o\ dS = \omega\varepsilon_o\ E_o^{av}\ A \end{aligned} \qquad (6)$$

This relation between I_{sc} and E_o^{av} was shown by Kaune (1981) to provide a useful method for calculating the average electric field over the surfaces of humans and other animals in a high-voltage electric field. For a 70-kg man with a body surface area of 1.8 m^2, the short-circuit current in a 10-kV/m field is about 160 µA and the value of E_o^{av} predicted from equation (6) is 27 kV/m.

Contact Currents and Electric Shock Phenomena

Ungrounded metal objects within a high-voltage field can acquire a large surface charge and a high electrical potential relative to ground. Current flow is initiated when contact is made with the object by either a grounded or ungrounded person. The issue of electric shocks is a major practical concern in the vicinity of a high-voltage transmission line. Several classes of ungrounded or poorly grounded objects that represent a source of significant contact currents include large vehicles such as buses and tractor-trailers, large buildings with inadequate grounding of metal gutters and downspouts, wire fences and metal pipelines with long ungrounded sections, and farm equipment such as combines and tractors.

The severity of an electric shock depends upon a number of factors, including grounding conditions, magnitude of the contact current, duration of current flow and body mass. For adult humans insulated from ground by standing on a 0.3 m platform, the average body-to-ground capacitance was found to be approximately 275 pF and a shock sensation was observed at voltages exceeding 1 kV (Barthold et al., 1972). The threshold contact currents required to elicit both mild (perception) and severe (respiratory arrest and ventricular fibrillation) shocks have been well-studied in humans and in several species of animals with varying sizes. Early studies were conducted in the 1940's and 1950's by Dalziel, Kouwenhoven and others, and in recent years several summaries have been made of threshold currents for inducing electric shock phenomena in humans (Barthold et al., 1972; IEEE, 1978, 1984). Table 2 summarizes the body currents that elicit mild to severe responses. Currents above the 10 mA level represent a serious risk since the "let-go" threshold may be exceeded and the individual might not be able to release a charged object because of involuntary muscle contractions. In general, the contact currents that elicit reactions in 0.5 percent of adult human subjects are two to three times less than the levels which produce a 50 percent response. Also, the estimated level of the let-go current in small children is approximately one-half as large as that for an adult man.

In order to limit hazards from contact currents, many states have adopted regulations based on the National Electrical Safety Code (NESC) prepared by the American National Standards Institute. The NESC requires utility companies to design transmission lines in a manner that limits the short-circuit current to ground from the largest anticipated vehicle (or other objects) to less than 5 mA. In practice, this limits

TABLE 2 Human Reactions to 60Hz Electric Currents

Reaction/Sensation	Average r.m.s. current (mA) to elicit effect at the 50 percent response level	
	Women	Men
Grip perception	0.73	1.10
Painful shock	6	9
Let-go threshold	10.5	16
Respiratory tetanus[a]	15	23
Ventricular fibrillation[a]	210	275

[a] Estimated values based on experimental animal studies and/or limited observations on humans.

the electric field over roadways to approximately 7 to 8 kV/m. It is important to realize that the NESC limit on I_{sc} will reduce contact currents between a person and a charged object to levels that are usually much below 5 mA because of impedance between the person and object, as well as person-to-ground and object-to-ground impedances.

Spark Discharges

Within a large electric field, capacitative spark discharges can occur between a person and a conductive object. A spark discharge can arise without direct contact if the person and object come close enough together (typically, $\ll 1$ cm) that the local electric field between them exceeds the dielectric breakdown level for air (3×10^6V/m). Human reactions to spark discharges can be described either in terms of an energy threshold given in millijoules (mJ) or a charge threshold given in microcoulombs (μC). A comparison of these thresholds is shown in Table 3 (data from IEEE, 1984).

For small objects with capacitance less than approximately 600 pF, the energy criterion appears to give the best fit to data on human perception to spark discharges (IEEE, 1978). For larger objects (such as automobiles) with a greater capacitance, the charge criterion gives a better fit to the data than the energy criterion.

TABLE 3 Perception Thresholds for Spark Discharges

Reaction/Sensation	Threshold for reaction in 50 percent of adult men tested	
	Energy (mJ)	Charge (μC)
Fingertip touch perception	0.14	0.3
Fingertip touch annoyance	1.3	0.9

Internal Electric Fields Induced in Living Objects Within a High-Voltage Field

The relative magnitudes of the normal components of a 60-Hz electric field existing outside and inside the air/body surface can be calculated from equation (4):

$$|\hat{n}\cdot E_i| \simeq j\omega\epsilon_o/\Lambda_i)\,|\hat{n}\cdot\vec{E}_o| \simeq 3\text{x}10^{-8}|\hat{n}\cdot\vec{E}_o| \qquad (7)$$

It follows from equation (7) that the magnitude of the internal field is exceedingly small. For example, the magnitude of E_o at the top of the head is about 200 kV/m for a man standing in a 10-kV/m field, and E_i is approximately 6 mV/m. Since $\Lambda_i \simeq 0.1$ S/m for brain tissue, the induced current density in the head $J_i = \Lambda_i E_i \simeq 0.6$ mA/m^2 = 600 nA/cm^2.

The values of E_i and J_i within different parts of the body exhibit large variations. Parts of the body with small cross-sectional areas, such as the neck, knees and ankles, have the largest current densities. These regions, in effect, "concentrate" the induced current density.

Two techniques have been applied to the direct measurement of induced electric fields in different anatomic locations within electrically conducting scale models of man. Guy et al. (1982) used thermography to quantify the current distribution in homogeneous scale models exposed to a high-intensity 57.3 MHz field. The measured current densities were then corrected for frequency and for the difference in electrical conductivity at 60 Hz relative to 57.3 MHz in order to estimate the current densities induced by a power-frequency field. A second and more direct approach was taken by Kaune and Forsythe (1985), who used an electric field probe to estimate the induced fields and current den- sities in different regions of saline-filled human models exposed to a 60-Hz electric field. The results of current density measurements by Guy et al. (1982) and by Kaune and Forsythe (1985) in several anatomic locations within conducting scale models of man are summarized in Table 4. The measured and theoretically predicted current densities are, in most cases, in reasonable agreement.

INTERACTION OF POWER-FREQUENCY MAGNETIC FIELDS WITH MAN AND OTHER LIVING ORGANISMS

A fundamental difference in the interactions of power-frequency electric and magnetic fields with living objects is the fact that the magnetic field is neither enhanced at the body surface nor attenuated within the body. The magnetic flux density, $\vec{B}$, is related to the magnetic field intensity, $\vec{H}$, through the relationship $\vec{B} = \mu\vec{H}$, where μ is the magnetic permeability. Because the magnetic permeability of living tissue is nearly identical to that of air, it follows that the magnetic flux density external to the body, $\vec{B}_o$, is approximately equal to that within the body, $\vec{B}_i$, in an ELF field. At high frequencies, where the skin depth is comparable to or less than body dimensions and reflection losses cannot be neglected, this relationship between $\vec{B}_o$ and $\vec{B}_i$ will no longer hold. At power frequencies, however, the skin depth is greater than 50 meters and reflection losses at the surface can be neglected, so that the relation $\vec{B}_o = \vec{B}_i$ is valid to a high degree of accuracy.

The electric field induced within tissues exposed to an ELF magnetic field can be calculated from Faraday's law

$$\oint \vec{E}\cdot d\vec{l} = -d/dt\iint\vec{B}\cdot d\vec{S} \qquad (8)$$

where $d\vec{l}$ is a vector element of length directed along the closed loop over which the line integral is calculated, and $d\vec{S}$ is a differential area vector normal to the surface bounded by the closed loop. For the specific case of a circular loop with radius R and a spatial orientation that is orthogonal to the external field B_o, the magnitude of the induced internal field field, E_i, is given by

$$E_i = R\omega B_o/2 \qquad (9)$$

The induced current density, J_i, is equal to

$$J_i = \Lambda_i E_i = R\omega\Lambda_i B_o/2 \qquad (10)$$

Both E_i and J_i are therefore linear functions of the field frequency and the radius of the loop.

TABLE 4 Calculated and Measured Current Densities in Human Models

Body location	Average r.m.s. vertical J_i (nA/cm^2) for E_o = 10 kV/m		
	Calculated	Electrical measurement[a]	Thermography[b]
Neck	550	375	410
Chest	190	260	380
Abdomen	250	330	---
Ankle	2000	---	1950

[a] From Kaune and Forsythe (1985).
[b] From Guy et al. (1982).

It is of interest to calculate the relative magnitudes of the current densities induced by the electric and magnetic fields associated with a 60-Hz high-voltage field. Consider, for example, a 10-kV/m, 0.5-G power-frequency field that is vertically incident on the head of a standing human (R = 0.08 m and Λ_i = 0.1 S/m). From equation (10), the magnetically-induced current density circulating around a loop at the perimeter of the head is equal to $J_{i,B}$ = 7.5 nA/cm^2. The electrically-induced current density, $J_{i,E}$, is directed along a vertical axis within the head and has a magnitude of 60 nA/cm^2. The electrically-induced current density is therefore eight times as large as that induced by the magnetic field, and has a different spatial orientation within the head.

In terms of direct physical hazards from the magnetic fields associated with high-voltage, power-frequency systems such as transmission lines, the currents induced in long stretches of ungrounded metal conductors can present a risk of electrical shock. This situation could arise, for example, in the case of an ungrounded metal fence or a pipeline running parallel to a high-voltage transmission line. As in the case of shocks from electrically-charged conductors, this hazard can be avoided by adherence to proper grounding practices.

Another aspect of magnetic field interactions that should be noted is the inability of humans to perceive relatively large power-frequency magnetic fields, in direct contrast to the sensory stimulation provided by power-frequency electric fields with high intensities. In a careful study involving more than 200 human subjects exposed to 60-Hz magnetic fields with r.m.s. intensities up to 15 Gauss, Tucker and Schmitt (1978) found no evidence for field perception when they had successfully removed all sources of auxiliary clues such as vibration and audible noise associated with activation of the magnet coils.

CORONA AND RELATED PHENOMENA

Corona discharges occur at locations on high-voltage conductors where the surface fields exceed the dielectric breakdown level of air. Enhanced local fields that produce corona arise at surface irregularities caused by such factors as nicks in the conductor, attached insects, or hanging water drops. Corona energy loss occurs primarily as heat, but acoustic, electromagnetic and photic energy also result from a discharge. These modes of energy loss can result in audible noise, radio and television interference, and the production of oxidant gases such as ozone. A brief description of these secondary effects of corona are given in the following sections.

Audible Noise

Corona-generated audible noise covers the entire audio frequency spectrum up to 20 kHz, and is present as both discrete tones and as broadband noise. The most noticeable discrete tone is at 120 Hz, but the greatest annoyance to humans results from the broadband noise at frequencies above 500 Hz.

The audible noise level from corona on high-voltage conductors is strongly dependent on the moisture content of the air. Audible noise levels are normally expressed in decibels (dB) relative to a reference level of 20 micropascals ($= 2 \times 10^{-5}$ newton/m^2), and they are "A-weighted" to correspond to frequency-dependent variations in human auditory sensitivity. The A-weighted sound pressure levels above which complaints arise is approximately 52 dB, and levels above 58 dB are generally objectionable (Perry, 1972). For comparison, the normal conversation level between two individuals spaced two meters apart in an outdoor environment is about 55 dB. The Environmental Protection Agency has recommended that the average noise level from corona discharges should not exceed 55 dB in a rural environment. In addition, eleven states have established permissible audible noise limits that vary as a function of frequency and encompass a range of sound pressure levels from 40 to 70 dB.

Radio and Television Interference

Corona-generated electromagnetic noise in the low (30 to 300 kHz), medium (300 kHz to 3 MHz) and high (3 to 30 MHz) frequency ranges can interfere with amplitude-modulated radio signals. In the VHF range from 30 to 300 MHz, noise from corona and from discharges at mechanical gaps in transmission line conductors can interfere with AM television video signals. Frequency-modulated radio signals and television audio signals are both immune to this type of noise.

The electromagnetic noise produced by corona and gap discharges is expressed in dB relative to a reference field strength of 1 μV/m. The extent of radio and television noise interference is influenced by several factors related to transmission line design (e.g., the mechanical condition of conductors and their voltage, size, spacing and height above ground), and by meteorological factors such as the moisture content of the air. In general, noise in the AM radio band produces little interference at levels below 54 dB, and noise in the VHF band that is less than 47 dB does not appreciably interfere with television video signals (IEEE, 1984).

Radio and television noise interference associated with transmission lines is currently not regulated at the state or federal levels. Thirty-two states require utilities to perform an environmental assessment for new high-voltage lines, and to limit noise levels in compliance with the Federal Communication Commission code which states that 24 dB is a satisfactory signal-to-noise ratio for radio broadcasting.

Ozone and Other Oxidants

Corona discharges from high-voltage conductors produce ozone (O_3) and other oxidants such as nitrous oxides (Roach et al., 1978). From theoretical considerations, the maximum possible concentration of corona-generated ozone near a 765-kV line under worst-case conditions (rain and a low wind velocity) is about 7 to 9 p.p.b. Actual measurements under worst-case conditions indicate that ambient ozone concentrations attributable to transmission lines do not rise above 2 p.p.b. This level is well below the Environmental Protection Agency Ambient Air Quality Regulation which limits ozone to a maximum one-hour concentration of 80 p.p.b. (not to be exceeded more than once per year).

Other oxidants produced by corona discharges such as oxides of nitrogen are present near high-voltage lines in concentrations that are 5 to 20 times less than the concentration of ozone. The concentrations of these oxidants produced by corona are also far below the permissible limits prescribed by the EPA Ambient Air Quality Regulations.

PHYSICAL HAZARDS ASSOCIATED WITH POWER-FREQUENCY ELECTROMAGNETIC FIELDS

Studies during the past decade have demonstrated several physical phenomena associated with high-voltage electromagnetic fields that are potentially hazardous to humans and to various other life forms. In this section a brief summary will be given of electromagnetic interference (EMI) effects on cardiac pacemakers, as well as various direct effects of high-voltage fields on animals and plants.

Pacemaker Interference

Certain types of modern cardiac pacemakers exhibit malfunction in response to EMI produced either by endogenous myopotentials or by external sources such as high-voltage systems. The modern implantable pacemakers are microprocessor-controlled and function in a "demand" mode in which stimulatory pulses are delivered to the heart only if it fails to exhibit intrinsic electrical activity. The endogenous cardiac activity is detected by a signal sensing circuit in order to avoid competitive pacing between the pacemaker's stimuli and the heart's intrinsic activity. The modern pacemakers also contain a noise detection circuit that can discriminate electric fields with different frequencies and waveforms than those associated with the heart's bioelectric activity. When EMI is sensed, the demand pacemaker reverts to a fixed-rate pacing mode which may be asynchronous with the normal cardiac activity. This pacing mode is frequently referred to as the "reversion" or "noise" mode of operation, and can be undesirable if the pacemaker signals are competitive with the intrinsic cardiac electrical activity.

Two different configurations of electrode leads are used in pacemakers, and these have very different sensitivities to EMI. In one style, termed the "bipolar" design, both leads are implanted within the heart at a typical separation distance of 3 cm. In the second style, termed the "unipolar" design, the cathode lead is implanted in the heart and the pacemaker case serves as the anode. Because of the considerable physical separation of the anode and cathode leads in the unipolar design, this type of pacemaker provides a large antenna for the reception of EMI. Of the two designs for pacemaker electrode configurations, only the unipolar type has been found to be sensitive to EMI. Among the 350,000 to 500,000 individuals in the U.S. that have implanted pacemakers, approximately 50 percent have models with the unipolar electrode design.

During the past decade several laboratory tests and studies on pacemaker patients have been conducted to assess the response of different pacemaker models to power-frequency electric and magnetic fields (Jenkins and Woody, 1978; Butrous et al., 1982, 1983 a,b; Griffin, 1985). Two types of pacemaker malfunctions have been observed in response to EMI: (1) an aberrant pacing rate, with irregular or slow pacing, and (2) reversion to fixed-rate (asynchronous) pacing. The probability that a malfunction will occur in the presence of an external electromagnetic field is strongly dependent on the pacemaker model, since some manufacturers have incorporated a feature into their pacemakers that automatically decreases the sensitivity of the amplifier circuit when EMI is sensed. These specific brands of pacemaker thereby avoid reversion to an asynchronous mode in response to EMI.

The range of power-frequency field strengths that cause reversion to an asynchronous mode of operation has been characterized for unipolar pacemaker models that are vulnerable to EMI. Power-frequency electric fields with intensities in the range of 3 to 20 kV/m (producing body currents of 26 to 203 μA) have been found to cause reversion or an aberrant pacing rate in 15 of 16 models that were tested (Butrous et al., 1983b). With all but two of the pacemaker models, both of which were produced by the same manufacturer, fields greater than 5 kV/m were required to produce a malfunction. Power-frequency magnetic fields ranging from 1.1 to 4 G were found to produce reversion to an asynchronous mode or to produce abnormal pacing characteristics in 77 percent of the pacemakers tested, with the average threshold field level for an effect being 2.1 G (Jenkins and Woody, 1978). The levels of power-frequency electric fields that were observed to produce pacemaker malfunction are within the range of field levels associated with high-voltage power lines and other types of electrical systems. The occurrence of EMI effects on the pacemakers of workers at electrical substations has recently been described by Butrous et al. (1983a). In contrast, pacemaker malfunctions produced by power-frequency magnetic fields require field intensities that are greater than those associated with high-voltage transmission lines and most other types of electrical systems.

Griffin (1985) has estimated the total population of pacemaker patients in the U.S. who might be at serious risk to the effects of EMI. He assumed that (1) 350,000 to 500,000 individuals wear pacemakers, (2) that 50 percent are of the unipolar design, (3) that 10 to 20 percent of the unipolar pacemakers are highly sensitive to EMI, and (4) that 20 to 25 percent of the patients with sensitive pacemakers are totally dependent on the pacemaker to sustain their cardiac rhythm. With these assumptions, it can be calculated that approximately 3,500 to 12,000 pacemaker wearers might be at serious risk to EMI. However, it must be borne in mind that only a small fraction of the individuals at risk are likely to encounter a source of EMI such as a high-voltage transmission line during the time periods when their cardiac function is totally dependent on an implanted pacemaker. The above estimate of the population at risk must therefore be regarded as an upper bound that perhaps greatly overestimates the actual probability for the occurrence of a potentially fatal pacemaker malfunction in response to EMI.

There are at the present time no federal or state regulations requiring manufacturers to use procedures that would ensure pacemaker immunity to EMI. However, as discussed earlier some pacemaker manufacturers have used state-of-the-art technology to provide immunity from the effects of EMI, and it would clearly be advisable if other pacemaker suppliers were to follow this example.

Physical Hazards to Animal and Plant Life

Three types of power-frequency electromagnetic field effects on living systems that are well understood in terms of the relevant physical interaction mechanisms will be discussed in this section. These three phenomena are (1) step potentials in beehives, (2) stray voltage effects on livestock, and (3) corona discharges on the tips of plant leaves.

Beehives in strong electric fields can develop significant electrical potential differences over dimensions that are comparable to the length of a bee's body. This potential difference is called a "step potential" since the bee experiences a shock each time it takes a step. The threshold field level is in the range of 1.8 to 4.1 kV/m for inducing physiological and behavioral changes in the honeybees such as weight loss and abnormal deposition of propolis at hive entrances (Greenberg et al., 1981). At a field level of 7 kV/m, which produces a total hive current of 90 A, there is a significant decrease in foraging by the bee colony, a loss of queens, and a greatly reduced survival rate. The solution to this problem is straightforward, since a grounded metal cage or screen placed over a hive that is located in the vicinity of a high-voltage transmission line will reduce the field within the hive to a level that is not harmful.

Another direct effect of power-frequency electric fields on animals results from "stray voltages" that can cause microshocks upon contact with metallic surfaces on devices such as automatic feeders, etc. (Gustafson and Albertson, 1982). These stray voltages arise from small potential differences that develop between a grounded neutral conductor and the true earth ground (neutral-to-earth voltages). Livestock such as dairy cattle can perceive low-level shocks from stray voltages, with a resulting effect on productivity and health. Stray voltage sources are in the electrical distribution system rather than the primary electrical supply lines, and these voltages are not a problem directly associated with high-voltage transmission lines. The mitigation of neutral-to-earth voltages can be achieved by various methods which include modification of the neutral voltage system, altering the total electrical load, or modifying the conducting surfaces present in areas where stray voltage problems are encountered.

The sharp tips of leaves on certain species of plants can be damaged by corona discharge when the plants are in high-voltage fields at intensities exceeding 20 kV/m (Johnson et al., 1979). However, as recently reviewed by Graves et al. (1985b), a number of studies have failed to detect any adverse effects of power-frequency fields up to 30 kV/m on plant life. The plant parameters that were found to be unaffected by high-voltage fields include growth rate, seed production and germination, and physical characteristics such as height, mass and leaf area.

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BIOLOGICAL EFFECTS OF ELECTRIC FIELDS

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INTRODUCTION

Extremely low frequency (ELF) electric and magnetic fields, many times above ambient levels, occur in the vicinity of existing and proposed energy generating, storage, and transmission systems. Concern over the possible deleterious health effects due to exposure to these electric fields was first expressed in the late 1960s and early 1970s. In an early Soviet study, a variety of neurological symptoms, including headaches, excitability, fatigue, and nausea, were reported in workers at ultra-high-voltage (>45 kV) switchyard stations (Asanova and Rakov, 1966; Korobkova et al., 1972). Although it is not possible to conclude that the reported functional changes resulted from exposure to the electromagnetic fields, the research findings led to additional research in the USSR and throughout the rest of the world. Numerous studies were initiated in a wide range of investigations to assess the potential biological consequences of exposure to static and ELF electromagnetic radiation (e.g., Singewald et al., 1973; deLorge and Marr, 1974; Kouwenhoven et al., 1967; Knickerbocker et al., 1967; Graves et al., 1979; Knave et al., 1979; Cerretelli et al., 1979; Phillips et al., 1979a, 1981). These studies included epidemiological investigations of people exposed, both occupationally and nonoccupationally, to electric fields, as well as experiments on laboratory animals.

Several major symposia and reviews of the literature have been published in recent years (AIBS, 1985; Anderson and Phillips, 1985; Bridges, 1975a,b, 1978; Sheppard and Eisenbud, 1977; National Academy of Sciences, 1977; Michaelson, 1979; Phillips et al., 1979b; IITRI/EPRI, 1979; Male and Norris, 1980; WHO, 1984; Lee et al., 1982; Sheppard, 1983). These reviews address a broad range of research interests and represent a considerable volume of literature, particularly with regard to experimental animal studies.

This paper represents a cursory overview of research concerned with the biological consequences of exposure to extremely low frequency radiation primarily at 50 and 60 Hz. It summarizes epidemiological and clinical studies conducted to date and presents a somewhat more extensive examination of the results of studies using experimental animals. In an attempt to help the reader evaluate and interpret those results, a discussion of current concepts on possible mechanisms and future directions of research are presented.

EPIDEMIOLOGICAL STUDIES

There is little quantitative, unbiased data that can be reliably interpreted from epidemiological studies. Two major problems have plagued many of the human exposure studies to date: (1) failure to obtain quantitative data on the level and duration of exposure, and (2) failure to include an appropriate control group that is comparable in all respects to the exposed group, except for exposure to the electromagnetic field. While this does not necessarily invalidate the results of such studies, it is important to be aware of these potential problems when evaluating the results.

The earliest investigations of human exposure to power-frequency (50 Hz) electric fields were conducted in the Soviet Union in the early 1960s (Asanova and Rakov, 1966; Korobkova et al., 1972). These surveys of workers in high-voltage switchyards indicated a variety of subjective symptoms in the cardiovascular, digestive, and central nervous systems subsequent to prolonged exposure of switchyard workers to electric fields (up to 26 kV/m). More recent work in the USSR has raised some questions as to the cause of the observed effects. It has been suggested that the observed effects might be the result of exposure to microshocks or kerosene vapor rather than exposure to electric fields (Danilin et al., 1969; Krivova, 1968; Savin et al., 1978; Bourgsdorf, 1980).

Results from the earliest comparable studies in the United States failed to confirm those of the USSR studies. Kouwenhoven et al. (1967) and Singewald et al. (1973) studied ten linemen exposed over a four-year period to unperturbed fields of up to 25 kV/m and observed no correlation between exposure and the health of the subjects. This study, however, included only a small number of subjects, and descriptions of the experimental protocol and results are incomplete.

Studies of agricultural workers exposed to electric fields have been conducted in both the USSR and the United States. Dumansky et al. (1977) found no effects in farmers exposed to ELF fields of 12 kV/m for 1.5 hours per day, but fatigue and mild physiological effects were reported by workers exposed in similar environments to 16 kV/m. Eighteen farmers in Ohio working around 765-kV transmission lines reported no adverse health effects (Busby et al., 1974). Similarly, a study of 70 families living and working close to 200- and 400-kV lines in France revealed no problems attributable to electric-field exposure (Strumza, 1970).

Recent health surveys of occupationally exposed male workers include two especially thorough studies: Stoops and Janischewsky (1979), in Canada, and Knave et al. (1979), in Sweden. Both groups examined a wide range of biological variables and reported no significant health effects in nervous system function, blood chemistry, cardiovascular function, or general physical condition. Knave and coworkers reported differences between exposed and unexposed persons in scores obtained on psychological questionnaires (the exposed group scored better), and in fertility (fewer offspring and a lower percentage of male infants fathered by exposed workers). These differences, however, could not be ascribed solely to electric field exposure. The authors suggested that the differences might be due to variations in the level of education or other differences between the two populations.

Another study in Sweden (Nordstrom et al., 1981) describes preliminary work in which increased frequency of chromosome breakage was seen in a few workers exposed to 400 kV. In additional work, congenital deformities were found in 10 percent of 119 children of substation workers, whereas only 2.7 percent of unexposed workers showed such deformities (Nordstrom et al., 1983). Analyses of these data raise major questions in the interpretation of the results because the highest percentage of abnormal progeny appears to be related to job type rather than to level of exposure.

Recently, there has been a great deal of concern that exposure to ELF magnetic fields may be associated with the incidence of cancer. Wertheimer and Leeper (1979) have reported an increased incidence of leukemia among children in Denver, Colorado, whose homes had electrical wiring configurations suggestive of high-current flow. Presumably, these high-current configurations resulted in increased levels of magnetic fields in the homes. In a later study, Wertheimer and Leeper (1982) extended their research and found similar results in adults. A similar study by Fulton et al. (1980) in Rhode Island found no correlation between childhood leukemia and configuration of wiring in the homes. From a recent study in Sweden, Tomenius et al. (1983) report increased cancer rates in children whose homes had magnetic fields (50 Hz) greater than 3 mgauss.

Recent examinations of deaths in Washington State (Milham, 1982), Los Angeles (Wright et al., 1982), England and Wales (McDowall, 1983), London (Coleman et al., 1983), and New Zealand (Pearce et al., 1985) show an association between deaths due to cancer and occupations in electrical environments. Because of the limitations of such studies (see below), one cannot safely interpret the meaning of these findings. However, the clustering of such data from various mortality records strongly suggests that research is needed to investigate the potential relationship of very weak electromagnetic fields and cancer.

In summary, few physiological or psychological effects have been credibly related to electric-field exposure. Documentation of such effects, when reported, is often questionable for the following reasons:

- Monitoring of symptomatology is quite subjective and is frequently not well defined.
- Quantitative evaluation of effects is either not performed or is not clearly described.
- Appropriate control groups are not present.

o Electric and magnetic fields have been confounded by secondary factors (e.g., microshocks).

o Duration of observations is often limited to short time periods.

o Exposure levels vary widely and are not documented, making it difficult to estimate accurately the magnitude and duration of exposure.

o Many of the earlier studies have insufficient numbers of subjects to establish the statistical significance of putative effects.

ANIMAL EXPERIMENTS

Although the interaction of humans with electric fields is of prime importance and concern, many areas of biological investigation can be more efficiently and appropriately conducted using various other animal species. Experiments have been performed using rodents (rats and mice) primarily, but a wide variety of other subjects, including insects, birds, dogs, swine, and nonhuman primates, have also been used. A broad range of exposure levels has been employed, from a few volts/meter to more than 100 kV/m. An equally large number of biological endpoints have been examined for evidence of possible electric-field effects.

The review will be limited to studies concerning exposure to 60-Hz sinusoidal electric fields. The summaries are arranged according to the biological systems involved: behavior, biological rhythms, nervous system, endocrinology, bone growth and repair, cardiovascular system and blood chemistry, immunology and infectivity, fertility and reproduction, growth and development, mortality and pathology, cellular and membrane studies, and mutagenesis. These summaries indicate that, in most categories, some studies reported effects of exposure, while other studies reported no effects. There is general concurrence among scientists that exposure to 60-Hz electric fields produces biological effects; however, there is also a lack of unanimity as to whether any of these constitute a hazard. A brief synopsis and discussion of each area follows.

Behavior. Among the most sensitive measures of insult to a biological system are tests that determine modifications in the behavioral patterns of animals. This sensitivity is especially valuable in studying environmental agents of relatively low toxicity.

Animals detect electric fields at low field strengths. The threshold of detection reported by Stern et al. (1983) is between 4 and 10 kV/m in rats. Approximately 50 percent of exposed mice in a study by Rosenberg et al. (1983) responded to a field of 35 kV/m. Graves et al. (1978) reported that pigeons perceive electric fields at 32 kV/m. Pigs responded at about 30-35 kV/m (Kaune et al., 1978). Some indications of exposure-influenced activity were evident in rodents at even lower field strengths. Moos' data (1964) suggest increased activity (p 0.05 in two of five groups) in mice during the night, at field strengths of only 1.2 kV/m. Graves (1977), Rosenberg et al. (1983), and Hjeresen et al. (1980) have reported an orientation response, or increased activity at initial exposure, in rats and mice at 25-35 kV/m. This increased activity was transitory and disappeared within a relatively short time. In a well-documented study by Greenberg et al. (1979, 1981), increased activity was observed in honeybees in hives exposed to 4.2 kV/m. Exposed birds showed a behavioral pattern opposite to that of other animals: activity in chickens was suppressed during exposure to 26 or 40 kV/m (Graves et al., 1978; Bankoske et al., 1976); at higher field strengths (up to 80 kV/m), no effect was observed on their activity or general behavior (Graves et al., 1978; Bankoske et al., 1976).

Some interesting results have been observed in the preference/avoidance behavior of rats for remaining in or out of the electric field. At 100 V/m, no effect of exposure was evident, either in preference behavior or temporal discrimination (deLorge and Marr, 1974). However, at 25 kV/m, rats preferred to spend their inactive period _in_ the field, while at 75-100 kV/m they avoided exposure (Hjeresen et al., 1980). Swine (Hjeresen et al., 1982) remained out of the field (30 kV/m) at night but demonstrated no changes in activity, reaction to novelty or startle response.

Most of the behavioral work with nonhuman primates has been performed at very low field strengths (7-100 V/m) (deLorge 1972, 1973). Gavalas et al. (1970) and Gavalas-Medici and Day-Magdolino (1976) observed changes in interresponse time with exposure, but no other effects were seen. At a much higher field strength (30 kV/m), Feldstone et al. (1980) reported minor behavioral changes in exposed animals that appeared to be related to perception of the field.

In summary, the behavioral tests that most frequently showed an effect of exposure were those relating to detection of the field or to activity. Most other behaviors did not change with electric-field exposure at field strengths up to 100 kV/m.

Biological Rhythms. Few investigations have been conducted to examine the effects of 50- to 60-Hz electric fields on natural biological rhythms. Ehret et al. (1980a,b) used body temperature, metabolic rate and activity to examine both circadian and ultradian rhythms in rats exposed to 8.2, 33, 66, or 100 kV/m. They observed no effects due to exposure. Wilson et al. (1981, 1983) examined circadian rhythms in rats in a more direct fashion, measuring the cyclical pineal production of indolamines and enzymes. A significant reduction in the normal nighttime rise of melatonin and biosynthetic enzymes was observed in rats exposed to either 1.5 or 40 kV/m. Furthermore, the change in pineal indole response occurred only after 3 weeks of chronic exposure (Anderson et al., 1982).

Nervous System. Many of the reported effects of electric-field exposure appear to be related to the nervous system. This is not unexpected since the nervous system provides the sensory input from external stimuli. Although prior investigations reported no effects in the morphology of the central nervous system (CNS) of rats and chicks (Phillips et al., 1978; Carter and Graves, 1975; Bankoske et al., 1976), a recent study in Sweden (Hansson, 1981a,b) found significant changes in cell structure in the cerebellum of rabbits exposed to 14 kV/m. Exposed animals had abnormal morphology of the endoplasmic reticulum and many lamellar bodies, particularly in Purkinje cells of the cerebellum. Effects have also been demonstrated in the nervous system function of rats. Jaffe et al. (1980) showed a statistically significant increase in the excitability of synapses in the superior cervical sympathetic ganglia of rats exposed to 100 kV/m. Although no effect on the peripheral nervous system was seen, neuromuscular function was altered by exposure. A slightly faster recovery from fatigue occurred in one type of muscle following exposure to electric fields (Jaffe et al., 1981). Additional work has recently been reported (R. Jaffe, personal communication) on the effect of electric-field exposure on somatosensory receptors in rats. This investigator has identified a subcutaneous wide-field receptor that is stimulated by the electric field.

Endocrinology. Many of the major hormones have been examined for effects of electric-field exposure, particularly in rats and mice (Phillips et al., 1979a). Possible effects have been observed in only three: corticosterone, testosterone, and melatonin. Because corticosterone is produced by the body in response to stress, blood levels of the hormone are extremely sensitive to the method used in obtaining samples. Perhaps because of this sensitivity (rather than the effects of electric-field exposure), five laboratories have reported conflicting results. Marino et al. (1976b) reported depressed serum corticosterone in rats exposed to 15 kV/m. Hackman and Graves (1981) reported a transient increase in steroid concentrations in mice at the onset of exposure to 25 and 50 kV/m. In contrast, corticosterone levels were not affected in dogs exposed to 15 kV/m (Gann, 1976) or in rats exposed to 80 or 100 kV/m (Seto et al., 1982; Free et al., 1981). Lymangrover (1983) reported a threefold elevation in steroidogenic response of rat adrenal tissue exposed in vitro to 10 kV/m and treated with ACTH. No significant changes were observed in tissue response when exposure was 5, 100, or 1,000 kV/m. Serum testosterone levels were decreased from those of controls in rats exposed to 100 kV/m for 120 days but were not different from levels in controls in 30-day exposures (Free et al., 1981). Pineal melatonin levels were significantly reduced during the dark phase in rats exposed to 1.5 and 40 kV/m for 30 days (Wilson et al., 1981, 1983).

Bone Growth and Repair. In one report (McClanahan and Phillips, 1983), bone growth in rats did not appear to be affected by exposure to 100 kV/m. Two other studies (Marino et al., 1979a,b; McClanahan and Phillips, 1983) reported that bone-fracture repair was retarded in rats and mice exposed to 5 kV/m or 100 kV/m but not in animals exposed to very low (1kV/m) field strengths. McClanahan and Phillips (1983) suggest that exposure affects the rate of healing but not the strength of the healed bone.

Cardiovascular System and Blood Chemistry. Cardiovascular function has been assessed by measuring blood pressure and heart rate and by performing electrocardiograms (ECGs). Early studies reported, as possible effects of exposure, a decrease in heart rate and cardiac output in dogs exposed to 15 kV/m (Gann, 1976), and increased heart rates in chickens exposed to 80 kV/m (Carter and Graves, 1975). A more recent and comprehensive study in rats exposed to 100 kV/m showed no effect of exposure, even when the animals were subjected to cold stress (Hilton and Phillips, 1980). Cerretelli and Malaguti (1976) reported transient increases in blood pressure in dogs exposed to field strengths greater than 10 kV/m (50 Hz). Hilton and Phillips (1980) were unable to confirm a report by Blanchi et al. (1973) of changes in ECGs of animals exposed to 100 kV/m.

Serum chemistry appears to be unaffected by exposure. Several studies demonstrated this, including those in rats at 100 V/m (Mathewson et al., 1977), in rats at 8 kV/m (Marino and Becker, 1977), and in rats at 100 kV/m (Ragan et al., 1979). Hematologic data, however, present a more confusing picture. White blood cell count was often elevated in exposed populations of mice and rats (Graves et al., 1979; Ragan et al., 1983). Fam (1980), exposed mice to field strengths of 240 kV/m and found no differences in white or red cell count between exposed and sham-exposed male mice. However, he reported a significant decrease in white cells in exposed female mice. This study has not been replicated to assess the apparent contradiction with the other reports. The changes observed in white cell and, occasionally, in red cell counts were not generally consistent across studies and may represent spurious false positive findings. This was evident in the Battelle Pacific Northwest Laboratory (PNL) study (Ragan et al., 1983), in which apparent sporadic effects were not statistically significant when the appropriate multivariate analyses were used to evaluate hematologic and serum chemistry parameters.

Immunology. In a comprehensive investigation of the humoral and cellular aspects of the immune system, Morris and Phillips (1982) and Morris and Ragan (1979) observed no effects of exposure at very low field strengths (150 to 250 V/m) in mice or rats. No effects of exposure were observed in chickens, used to study the influence of electric-field exposure on infectivity by a leukemogenic virus (Phillips et al., 1981). Lyle et al. (1983), however, observed significant decrements in the cytolytic capacity of lymphocytes exposed to radiofrequency fields modulated at 60 Hz.

Fertility and Reproduction. Several studies have examined egg production and early development of chickens at low field strengths (Durfee et al., 1976; Kreuger et al., 1975; Bankoske et al., 1976). No effects of exposure were observed in hatchability, morphology, or development of chicks. Kreuger et al. (1975), however, reported reduced egg production in hens exposed at 3.4 kV/m. At higher field strengths (100 kV/m), no effects of exposure were observed on the reproductive ability, fertility, or mortality of rats and mice (Sikov et al., 1979; Knickerbocker et al., 1967). Results at Battelle PNL have indicated that sows exposed for extended periods are reluctant to breed and have a significantly increased incidence of teratisms in their offspring (Phillips, 1981).

Growth and Development. Many experiments have been performed to examine bees, chicks, mice, rats, and swine for effects of exposure

(100 V/m - 100 kV/m) on body weight. The majority of these studies (Mathewson et al., 1977; Kreuger et al., 1972; Greenberg et al., 1979; Graves et al., 1979; Bankoske et al., 1976; Phillips et al., 1979a, 1981; Fam, 1980) report no significant differences in growth between exposed and control populations. However, effects have been reported by Marino, who observed decreased body weight in rats and mice exposed to 5 and 15 kV/m (Marino et al., 1976a,b). Knickerbocker et al. (1967) also observed decreased body weight in male offspring of mice exposed at a very high field strength (160 kV/m). Hannson (1981a,b) reported a large (50 percent) decrease in the weight of rabbits exposed to 14 kV/m compared to unexposed controls. However, these rabbits were exposed out of doors, and he did not observe comparable growth stunting in laboratory-exposed animals. This discrepancy might result from an interaction between the electric field and the outdoor environmental conditions. Notable effects on development (as indicated above) have been seen in the study on the teratology of swine exposed for long durations to 30 kV/m (Phillips, 1981).

Mortality and Pathology. Studies by Moos (1964) and Phillips et al. (1979a) indicated no effect of either low (1.2-kV/m) or high (100-kV/m) field strengths on mortality rates in rats and mice. Again, results of studies by Marino et al. (1976a) differ: they report significant increases in mortality in mice exposed to 10 or 15 kV/m. Work by three other groups of investigators (Mathewson et al., 1977; Knickerbocker et al., 1967; Phillips et al., 1979a) shows no effect of electric-field exposure on tissue morphology of rats or mice.

Cellular and Membrane Studies. Several laboratories have examined the effect of electric fields on in vitro systems. Some obvious strengths of these studies are the large sample sizes available and the great degree of control over experimental variables. Also, these studies provide, better than whole-animal experiments, a fairly direct investigation of possible mechanisms of interaction between a biological system and the electric field. The most serious disadvantages with in vitro experiments are those of biological and physical dosimetry, and extrapolation. The dosimetric relationship between exposure in cellular systems and in whole animals is unclear, and extrapolation of results from the simpler systems to intact animals, particularly humans, is extremely tenuous.

Preliminary results of experiments using cultured Chinese hamster ovary (CHO) cells showed no effects of exposure to 3.7 V/m (in the medium) on cell viability, growth, or mutation rate (Frazier et al., 1982). However, Cell-plating efficiency, presumably reflecting an alteration in the cell membrane, was reduced in cells exposed to 60-Hz fields greater than 0.7 V/m in the medium. A number of studies have been performed, at the same field strength and similar frequencies, on slime mold (Marron et al., 1975; Goodman et al., 1976, 1979). After several months of exposure, frequency-dependent effects occurred in mitotic rate, cell respiration, and protoplasmic streaming. Interestingly, these effects were observed with both electric field and magnetic fields, alone or in combination.

Neural tissue in culture has been used in several studies, particularly those focusing on the interaction of electric fields with the cell membrane. Wachtel (1979) and Sheppard et al. (1980) demonstrated that the excitability of pacemaker neurons in Aplasia is altered by field-induced extracellular currents. Electrophysiologic data from mammalian brain slices indicate that a field of 0.1 V/m in the medium caused a potentiation of collective cell-firing in hippocampal neurons (Bawin et al., 1981).

An additional group of studies suggests that weak electric fields can affect biomolecular structure in quite specific ways. Several studies examined the "calcium efflux" from neural tissues exposed in vitro to low-frequency as well as to modulated radiofrequency electric fields. Effects were apparently restricted to certain "windows" in frequency and field strengths. Bawin et al. (1975) Bawin and Adey (1976), and Blackman et al. (1979, 1983, 1985) reported significant alterations in calcium exchange from cat and chick brain tissues exposed to fields as low as 10 V/m. Since calcium plays a key neuroregulatory role in many membrane processes, such field-induced changes in calcium exchange may result in significant changes in brain function. The occurrence of frequency and power windows, however, makes interpretation and extraction of the data difficult.

Mutagenesis. No effects have been observed that might suggest an effect of electric-field exposure on mutagenesis (Mittler, 1972; Phillips et al., 1979a; Frazier, 1982).

DISCUSSION

Numerous studies have been initiated to determine to what extent the electrical environment produced by power-line transmission poses a health hazard to living organisms (particularly to humans). The biological effects reported in many of the experiments have not yet confirmed any pathological effects, even after prolonged exposures to high-strength (100-kV/m) fields. Areas in which effects have been demonstrated appear to be primarily associated with the nervous system: altered neuronal excitability, altered circadian levels of pineal hormones, behavioral aversion to or preference for the field, and transient altered locomotor activity in the field. In the intact animal, it is not yet known whether these and other putative effects are due to a direct interaction of the electric field with tissue or to an indirect interaction, e.g., a physiological response due to detection and/or sensory stimulation by the field. The nature of the physical mechanisms involved in field-induced effects is obscure, and such knowledge is one of the urgent goals of current research.

Results to date have demonstrated various biological effects in specific species exposed in the laboratory to a wide range of field strengths. The extrapolation of specific effects that occur under controlled laboratory conditions to a general assessment of the health risk of a human population exposed to electric fields is very tenuous.

At least four considerations are critical to implement such an extrapolation with validity: (1) the relationship of specific laboratory conditions to the power-line environment; (2) the relevance of effects in laboratory animals to other species, particularly humans; (3) dosimetric considerations, including scaling between species; and (4) an evaluation of the biological consequences of observed effects.

Many of the experiments reviewed in this report were designed to study the effects of electric fields under laboratory conditions. In most cases, field strengths that were employed corresponded to those characteristic of power lines, but factors other than the electric field may have affected experimental results. Such factors, e.g., ozone, ions, spark discharge, audible noise, etc., can produce biological effects and must be recognized and controlled to determine whether the electric field is actually the agent responsible for observed effects.

Any extrapolation of effects from one species to another depends on the mechanism by which the field exerts its influence on the biological system. This requires a knowledge of the biological structures and functions involved, as well as dosimetric scaling of exposure from the test animal to another species.

Perhaps most difficult is the question of when the occurrence of a "biological effect" constitutes a health hazard. Specific answers may be forthcoming; however, experimental results to date show no clear implications of health risks to humans exposed to 60-Hz electric fields.

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ELECTRIC AND MAGNETIC FIELD RESEARCH PERSPECTIVES

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INTRODUCTION

The Electric Power Research Institute (EPRI) is funded on a voluntary basis by electric utilities in the United States. The primary objective of EPRI is to develop technology and information that will enable electric utilities to generate, transmit, and distribute electricity more economically and with less of an effect on the environment.

It has been asked why electric utilities would want EPRI to do research on environmental issues that might result in additional operating constraints. EPRI's board has endorsed the following rationale:

1. There are no secrets in the scientific community; therefore, while EPRI's research may identify new problems, these would have been found later in any case;
2. Because retrofitting is always more expensive, it is better to build facilities appropriately in the first place. Therefore, it is in the industry's interest to know what requirements need to be met as early as possible;
3. There is often poor quality environmental information. By funding research, adequately the industry is likely to have the correct facts in hand as issues come up;
4. No industry leader wants to do harm to the environment. However, there are often questions on what degree of environmental protection is needed. By funding research, the industry can be more assured of meeting its environmental responsibilities.

EPRI was created, then, to provide technologies and information. But EPRI is not involved in policy advocacy; that is the role of the industry trade association and individual utilities. However, one would hope that the facts developed by research would help bring about more rational policies. In this spirit, EPRI's research results are made available to anyone interested, and researchers under contract to EPRI are free to report their results in the open literature beyond the EPRI report required of most contracts.

Electric and magnetic fields research, the subject of this paper, has been carried out in the spirit of this approach. There appeared to be a question as to whether electric and magnetic fields from electric utility facilities could adversely affect the environment. A research program was developed to elucidate this issue.

This paper is structured in four parts. Part I reviews the basic premises for the research plan and the primary philosophy of approach. Part II briefly reviews EPRI's research projects and highlights the results in a few of the most important projects. Part III highlights the other major research sponsors in this area and describes the coordination that is taking place. Part IV identifies EPRI's perspective on further research needs and stresses some of the inherent limitations to this field of investigation.

PHILOSOPHY OF ELECTRIC AND MAGNETIC FIELD RESEARCH AT EPRI

It is clear that electric and magnetic fields occur when electricity is transmitted over cables. These generally increase with voltage and current, respectively. In present construction practice, the higher the voltage used the higher the lines and wider the right-of-way needed. With alternating current (ac) lines of the highest voltage used today (765 kV), the highest electric fields under these lines are about 10 kV/m. Magnetic fields are typically on the order of tenths of a gauss. With direct current (dc) lines, air ions are created that can, under the right conditions, drift down to the right-of-way at measurable concentrations above background levels. They can also attach to particles and be advected downwind.

Exposures to these electric and magnetic fields and air ions can occur not only to those under transmission lines, but also to electrical employees, to other industrial employees, and to the general public in their homes and offices. Whether such exposures cause a significant risk is the major issue to be investigated. There is also the question of what environmental effects could be caused by such fields to domestic or wild animals or to cultivated or wild plants.

Studies have shown that humans can perceive electric fields at roughly 5 kV/m; animals are usually more sensitive, indicating sensation to the field at levels as low as 1 kV/m. But whether there are serious effects from such exposures is the principal focus of the research. Given the substantial increase in exposure to such fields over the last 40 years, if there were any effects they must be relatively subtle. Otherwise, there should have been an obvious increase in morbidity or mortality correlated with this presumed growth in exposure.

Also, systematic reviews of the research literature in this area led to the conclusion that no effects had been clearly demonstrated. However, there were many ambiguous results that needed clarification. It was with this history that EPRI's electric and magnetic field research began in 1974.

RESEARCH ALTERNATIVES AND RESULTS

EPRI's research program can be divided into four types: toxicology, epidemiology, exposure measurement, and risk assessment/management. By far the greatest effort so far has been placed on the toxicologic approach. The exposure measurement effort is being increased now. Only a little work has been done in the other two areas. Below are descriptions of the major projects and results in each of these areas.

Toxicology

One of the initial concerns was the potential harmful effects of electric fields on crops. Moreover, if effects could be demonstrated and mechanisms understood, it could simplify the design of experiments on higher forms of life. Over a seven-year period Dr. Guy McKee at Pennsylvania State University and Mr. Terry Reed from Westinghouse Corporation exposed thousands of living plants of many diverse species to intense 60-Hz electric fields. Exposures lasted for periods of a few seconds to several months, and field strengths of up to 50 kV/m were used. To control random variability not associated with electric field effects, all plants were grown either in a greenhouse or in a plant growth chamber where such environmental factors as temperature, photoperiod, soil fertility, soil moisture, diseases, and insects could be controlled. All tests were replicated. The only adverse effect found was the destruction of minor amounts of tissue on pointed or sharp parts such as leaves, needles, or thorns. It was concluded that there is little potential for serious ecological or economic damage.

Another approach was to study honeybees. It was thought that their highly developed organization and signaling system might yield insights into the neural effects of electric and magnetic fields. Moreover, early studies had reported that colonies under a 60-Hz, 765-kV transmission line with 7-kV/m fields were adversely affected, and, in fact, experienced colony failure. Also, there were reports of experiments showing change in bee behavior under electric fields.

Dr. Greenberg and associates from BioConcern collaborated with engineers from IITRI on a multiyear study to explain these effects. By designing a porch at the entrance to the hives, the investigators were able to separate the electric fields from shock. They now report that colonies in which shock was eliminated showed no significant differences in hive weights and production at levels up to 100 kV/m for about 660 hours of exposure (Greenberg, 1985). (Shock is a matter of hive design and construction and, for commercial purposes, can be controlled.)

The broadest toxicologic approach was initiated in 1976 in coordination with the predecessor of the U.S. Department of Energy (DOE). Dr. Phillips and coworkers at Battelle Pacific Northwest Laboratories began investigating the possible effects of 60-Hz electric field exposure on small and large animal species. DOE sponsored the small animal work; EPRI sponsored the large animal work with Hanford miniature swine. (Swine were chosen because their weight and many of their physiological systems approximate those of humans.) This was a laboratory study and required the construction of elaborate, state-of-the-art facilities and the assembly of a dedicated, multidisciplinary team of scientists and engineers.

The swine were exposed about twenty hours a day, seven days a week, to uniform, vertical, 30-kV/m 60-Hz fields. (Given the relative configuration of the pig compared to man, this field strength best approximated the exposure of a person in a 10 kV/m external field. For a rat, the equivalent external field is approximately 65 kV/m.) The study included three filial generations. This was essentially a screening study with assessment of multiple parameters in a small group of animals. Few remarkable differences were observed between electric field exposed and control populations, although there was an increased incidence of morphological malformations among fetuses from two generations of female pigs bred after 18 months of exposure (Sikow, 1984). It is not clear that electric fields caused the developmental anomalies. A group of teratologists assembled to review the results concluded that the inherent high rate of malformations in this inbred line of swine was a likely explanation of the results. The report of that study is now being reviewed and should be available in the near future.

To clarify whether or not electric fields were the cause of a higher rate of malformations, it was decided to conduct a similar but larger study using rats. It was hoped that such a study would allow the use of sufficient animals to distinguish even a subtle effect from pure chance. Also, it would allow generalization of an effect across species, establishing an animal model amenable to hypothesis testing and to exploring the dose-response relationship of any effect to field strength and exposure duration. Preliminary studies using rats (Rommereim, 1984) and hamsters have already been conducted using existing facilities. Results were mixed and, because of the small sample size, cannot lead to meaningful interpretation.

EPRI has sponsored the construction of an elaborate small-animal caging and exposure system, and it plans to begin teratology studies of rats exposed to electric fields at two laboratories later this year. Field strengths above and below those used previously will be applied. Using the EPRI-supplied system, large enough groups of animals can be exposed to yield unambiguous results.

Epidemiology

Recent reports in the literature have suggested that groups hypothesized to have had higher exposure to electric fields may experience an excess risk of cancer. Interestingly, these diverse reports describe the excess cancers at different sites and of different types. Moreover, replication of some of these studies has not shown excess risk in otherwise comparable populations. EPRI has sponsored the review of several of these studies. In short, such epidemiologic studies, while creating a testable hypothesis, are weak in associating the specific causative factors. Perhaps most disturbing is the fact that virtually none provides a reasonable estimate of exposure. EPRI's efforts to develop personal exposure monitors are described later.

EPRI has sought a group for whom a reasonable exposure estimate might be made, one large enough to yield significant statistical results and for whom reasonably accurate health records might be obtained. Telephone linemen may be such a group. They have an incidental exposure to fields from electric power lines as they service telephone cable, frequently under live electric facilities. A reasonable exposure estimate may be possible. The group is relatively large, and the Bell System appears to have excellent records and is willing to cooperate. Dr. Matanoski at Johns Hopkins has been conducting a scoping study to determine the feasibility of a case control design with a defined subgroup of a population of workers. Results indicate that a study of leukemia risks among telephone linemen is feasible, and EPRI is considering conducting such a study.

This area of epidemiology is of such great concern that it is worth mentioning several other studies that have been initiated by others. The New York State Department of Health, in its Power Lines Project, is sponsoring two epidemiologic studies. One is being conducted in Denver by Dr. Savitz and coworkers from the University of Colorado. They are trying to determine if exposure to measured electric and magnetic fields in the homes of school-age children with cancer is different from that experienced by a comparison group. The Seattle study, conducted jointly by the Fred Hutchinson Cancer Research Center and Battelle Pacific Northwest Laboratories, is focusing on adults with leukemia. Again, they are exploring whether exposure to electric and magnetic fields within patients' homes is different from the exposure of a control group. In addition, Dr. Knave, at the Swedish Board of Occupational Safety and Health, is conducting three epidemiological studies to quantify health risks of electric utility workers: a 10-year prospective study; a registry study comparing incidences of cancer, miscarriage, and birth defects with employment categories; and a retrospective study of recently employed workers. Power-frequency field exposure is only one of 35 possible hazards being investigated.

Exposure Measurement

A major factor complicating these studies is the lack of exposure information both within the allegedly exposed groups and in the general population.

Further complicating this issue is the question of what fields should be measured: electric, magnetic, or both. There is no major problem measuring either electric or magnetic fields at a particular moment; instruments have long been available for that purpose. But researchers and other scientists are interested in such data as exposure over time or time exposed to fields of various intensities, and it is desirable that such determinations be made by a device carried on the human body. EPRI is developing instruments that can collect and process exposure data and also a methodology to estimate exposures of designated groups.

In 1979 the Bonneville Power Administration (BPA) started a project to determine the effects of occupational exposure to 60-Hz electric fields. A miniaturized electric field exposure monitor (EFEM) was designed and built by BPA to monitor continuously each day, the electric field environment of a worker. This unit, about the size of a cigarette pack, measures electric fields at the surface of the body where it is worn. More than 3,000 exposure days of data have been collected for several occupational categories. Measured exposures have been much less than estimates based on time in electric fields, averaging about 0.5 kV/m hour for 500- and 230-kV line crews, the highest exposed groups. A similar device was developed and employed by the Central Electricity Research Laboratory in Great Britain. Measured exposures were much less than expected from calculations and employee estimates.

ENERTECH and General Electric engineers have devised for EPRI an exposure measuring system that consists of a sensor vest, data collection instruments, and readout device. This unit has been used to measure electric fields varying from 1 kV/m to over 10 kV/m. Results are translated to time histograms of unperturbed field, surface field, internal current density, and total body current. One group that was studied using the vest was the typical farmer with a high-voltage line crossing his fields. The premise was that this was the group in the general public most likely to get the highest dosage over a year. The results were reassuring in that they showed that the calculated annual dose, based on measurements with the vest and extrapolation based on activity patterns, is at least two orders of magnitude--and possibly three--lower than that being applied to animals for toxicology studies. Interestingly, exposure to electric fields from appliances is probably higher for the farmer than exposure from the transmission line (Silva, 1985).

In 1982, a three-day measurements field test to evaluate and compare the EFEM and the vest system was held at BPA. Tests with a stationary subject wearing the instruments were used to demonstrate the effects of grounding, clothing, subject size, and meter location.

Dynamic occupational exposure simulations were used to compare accumulated measurements of exposure. The test showed both devices to be suitable for personal exposure studies. A report of that project will soon be available through EPRI (Bracken, 1985).

Under EPRI sponsorship, SRI investigators have made field measurements around homes. A device capable of wideband spectral analysis was used to determine the magnitude of the electric and magnetic fields at 60 Hz, harmonics of 60 Hz, and subfundamentals of 60-Hz. The primary aim of this study was to explore how the 60 Hz electrical environment is modified by household appliances. The 60-Hz line may be used as a carrier of signals between the utility and appliances. Electrical noise also was of interest.

EPRI has recently initiated an effort by Lawrence Berkeley to develop a small EFEM-like unit to measure magnetic field exposure for individual wear.* A microprocessor incorporated in the device will allow data on many characteristics of the field, such as time variability and integrated level, to be computed and stored in real time.

Now that there exists a variety of measuring devices, what does one do with them? In February of this year engineers involved in conducting measurements using all the available devices met for two days under EPRI and DOE sponsorship to determine what relationships exist between and among the various devices, accepting that there is not a standard way to make measurements but that each has limitations and advantages. A report of that workshop is being prepared.

ENERTECH has used the vest system to help develop an exposure model that can be used on a personal computer. Exposure data collected by the vest, together with time budget or labor analysis data and calculated electric field maps, constitute the model. As mentioned, the model has been extensively applied to the case of the typical farmer. The principles of the vest system have also been used to determine electric field exposure from electric blankets and water bed heaters.

However, much remains to be done to characterize exposures to the 60-Hz electric environment. Work to date has shown that electric fields from power lines are shielded by trees and structures, and that significant shielding may be provided by houses. Significant sources of electric fields have been identified within the typical home. None of this is well characterized. Beyond this, however, are issues such as time-of-day changes in fields and the unknown importance of integrated values compared to instantaneous peaks. Close coordination and communication between those making measurements and those using them to interpret biological results are essential to ensure that these issues are efficiently addressed.

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*Microprocessor Controlled Personal Dosimeter for Recording Low Intensity Power Frequency Magnetic Fields EPRI Agreement RP799-21.

Risk Assessment/Management

Risk assessment/management is both the starting point and the ending point of research on environmental hazards. EPRI's role in this area is twofold. First is the internal assessment to ensure that appropriate resources are devoted to the subject area. Given the uncertainties and lack of specific, documented effects from research in this area, the results of such a risk assessment highlight the need to respond to the public perception that there may be an effect. This has caused EPRI to place a high priority on finding such effects or showing, with reasonable probability, that the risk is extremely low. Second is structuring the assessment in such complex issues in a way that reasonable management decisions can be made. The latter, the decision itself, is not EPRI's role. No complete assessment procedure has been prepared. However, as a first step, a pilot study has been initiated to examine the nature of population exposure on a national basis.

COORDINATION WITH OTHERS

As listed below, there are several organizations significantly involved in electric and magnetic field research. The first reason for coordination is to optimize the limited resources by avoiding duplication. The second and equally important reason is to be aware of developments as early as possible by sharing results of projects approaching completion.

The principal agency in this field of research is the U.S. Department of Energy. DOE and EPRI have worked together closely both at the program level as well as at the general management level--up to the Secretary of DOE and president of EPRI. Communication between EPRI and DOE has minimized duplication of efforts and helped develop supportive projects. For example, sharing the responsibility for the rat and pig work demonstrated how the combined effort could be better than the individual effort of either organization. DOE has funded most of the laboratory screening studies using rodents and the behavioral experiments related to perception of the fields and to changes in circadian rhythms, as well as studies of the effects of corona noise on humans. As an example of coordination and cooperation, in 1983 EPRI and DOE held a joint review of contractors' research. In 1984 the New York State projects were also part of such a review.

The New York State Department of Health is administering a five-year program involving 15 projects ranging from cellular to human studies, generally with exposures to both electric and magnetic fields. Results from those projects should become available starting later this year.

There are also a number of individual utilities that are supporting research, for example, the Bonneville Power Administration, Southern California Edison, Commonwealth Edison, American Electric Power, and a consortium of Iowa and Illinois utilities.

EPRI is also aware of Western European research in this area. Program managers from both EPRI and DOE have visited European scientists; several of the Europeans have visited the EPRI and DOE laboratories, and some have participated in the contractors' reviews.

FUTURE NEEDS

More sound decisions can be made if better information is available. In this case, the relevant decision is whether or not the nation needs greater protection from electric and magnetic fields than it now has. EPRI's program is based on the premise that such additional information is vital to ensure that the public is not forced to pay for needless protection, and that if effects are demonstrated, that a rational management plan can be developed.

The most pressing need in EPRI's view is improved data on exposures from transmission lines, appliances in the home, and equipment in the workplace. With the recent growing concern about magnetic fields, the development of usable measurement instruments is particularly important. EPRI is currently spending most of its exposure resources on electrical field data base development but is expanding efforts on magnetic fields.

Because of the recent publication of epidemiological studies inferring a relationship between possible exposures and certain cancers, there is a need to develop this evidence further. EPRI is considering taking a careful look at one occupational group. However, more might be done with other groups. There should also be a responsible evaluation of the criteria used in such epidemiologic studies.

To some extent, suggesting mechanistic studies before effects are known is putting the cart before the horse. However, carefully designed studies of mechanism can be a help in designing whole animal experiments with reasonable hypotheses. Also, because of the difficulty of separating external sensory effects from those of induced internal currents, and the difficulty of separating electric fields from magnetic fields or replicating real-world combined exposures, some thought should now go into experimental designs that could accomplish these ends. For example, EPRI is planning work on current injection in laboratory animals to test the effects of known currents without confounding by the external sensations caused by an electric field.

Finally, there is a whole technology--high-voltage direct current transmission--that is becoming more prevalent. The environment associated with that system is very complex, consisting of static fields, air ions, ion currents, and charged aerosols. These factors have received little attention from the research community. EPRI has initiated an effort with Battelle Pacific Northwest Laboratories to design and develop a state-of-the-art exposure facility and to begin initial laboratory screening studies. The facility is completed, and laboratory studies are about to begin using both dc electric fields and air ions. In addition, EPRI has an ongoing behavioral study involving ions and relatively weak fields at the Institute of Basic Research. It is expected that the EPRI program in the dc area will expand over the next several years.

CONCLUSIONS

Unfortunately, it is impossible to prove through scientific findings that an environmental agent has no effect. For electric and magnetic fields, demonstrating that there is no risk is not a feasible goal. Yet, the utility industry recognizes that there is public concern, frequently exacerbated by stories of the most recent results from a laboratory or by contentions on the siting of a new transmission line.

The utility industry believes it owes its customers and the general public the best information possible on which to base decisions. Through EPRI, a program of research has been designed and implemented to yield the information needed to make better decisions. However, the public is also exposed to other fields, possibly larger in total integrated value than those caused by facilities directly owned by the electric utilities. Therefore, EPRI believes there is a shared responsibility to underwrite research into the possible effects from exposures to such fields.

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BIOLOGICAL SENSITIVITY TO LOW-FREQUENCY MAGNETIC FIELDS

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ABSTRACT

The authors review and discuss observational and experimental data that bear on the question of biological sensitivity to stationary and to low-frequency (100 Hz) magnetic fields. From examination of data in the archival literature, of data from recently completed studies by other investigators, and of original data from their studies, the authors reach the following conclusions: (1) Sensitivity to weak, time-varying fields on the order of the geomagnetic mean is a verfied biological datum. (2) A continuum of progressively greater uncertainty with respect to H-field sensitivity extends from lower to higher species. That is, some microorganisms, insects, and fish are demonstrably sensitive to magnetic fields; cases of select avian species such as the homing pigeon and the domestic chicken are less certain; and reports of mammalian sensitivity have yet to meet the critical tests of independent verification and peer consensus. (3) Commensurate, and inversely so, with the continuum of uncertainty is the degree of identifiability of biologically synthesized, ferrimagnetic domains in organisms with putative sensitivity to magnetic fields: Organized crystalline domains of magnetite (Fe_3O_4) have been isolated for some species of bacteria, bees, and fish; and they have been observed, but not consistently so, in the homing pigeon. In contrast, although magnetite and other paramagnetic compounds have been found in tissues of some marine and terrestrial mammals, their origin may well be artifactually ingested, ferromagnetic particles. And (4) the most convincing and consistent evidence of biological sensitivity is that to the natural stimulus--to the geomagnetic field. The stationary field, at densities typically near 0.05 mT, appears to serve as compass, possibly as map, for several species. There also is evidence that the much-less-intense, time-varying components of the natural field, which typically range between 0 and 30 nT and seldom exceed 50 nT, are detected by some species: Disruption of homing and migration by birds has been observed over terrestrial magnetic anomalies and during sunspot-associated magnetic storms. If a valid demonstration of NMI (natural magnetic interference), this disruption serves as a model for and mandates resolution of the open question of ecological perturbations by time-varying magnetic fields of human origin.

BIOLOGICAL SENSITIVITY TO LOW-FREQUENCY MAGNETIC FIELDS

Scope of Review

We present in this paper a synoptic review of data that bear on biological sensitivity of intact organisms to magnetic (H) fields. The focus is on fields at or near frequencies of electric-energy-delivery systems (i.e., 50 and 60 Hz). In addition to experimental data, findings from observations of airborne, terrestrial, and marine-dwelling species under the apparent influence of the natural (geomagnetic) field also are addressed. Physical principles and data are not addressed in depth as they have been treated in detail in several excellent reviews (Sheppard and Eisenbud, 1977; Sheppard, 1983; Tenforde, 1985), including that of Tenforde in the present volume.

Experimental Data

Invertebrates

Unicellular organisms. Blakemore (1975) has described magnetotactic bacteria that were later identified (Blakemore et al., 1979) as possessing organized domains of a ferrimagnetic compound magnetite. The utility of the domains is believed to lie in promotion of downward movements of this primitive marine organism, which feeds in the bottom mud of lakes and ponds. When transported from a normal habitat in, say, the northern hemisphere to the southern hemisphere, which is associated with a reversal of polarity of the Earth's magnetic field, the organism's downward movements are thwarted.

Amoebae that aggregate to form slime molds exhibited a reduced rate of mitotic activity, which was associated with a reduction in the rate of cellular respiration, during exposures ranging between 2 months and 5 years to 76-, 75-, 60-, and 45-Hz H-fields at 0.01 to 0.2 mT (milliteslas) and at 0.04 to 0.7 V/M, rms (Greenebaum et al., 1979). The decrease in respiratory activity ranged from 3 to 16 percent, was reliably different from that of otherwise identically incubated but non-exposed amoebae, and, curiously enough, was an all-or-none effect that was unrelated to density of the field within the tested range.

Insects. Several insects, including the termite, have yielded evidence of H-field sensitivity (Becker, 1976, 1977), but the honey bee has received the most extensive study (see, especially, the review by Gould, 1980). Like the magnetotactic bacterium, the honey bee possesses organized domains of magnetite that presumably can serve as compass, even map (Gould et al., 1978). Pertinent to the question of high-voltage transmission-line (HVTL) perturbations of the ecological system is a study, ostensibly based on controlled exposures of bee colonies to electric (E) fields at differing densities, from which emerged indications that adaptive behavior was disrupted by 60-Hz H fields. In the course of this study (Greenberg et al., 1981), a large number of colonies was situated at measured distances from a 765-kV HVTL. About half the colonies were electrically shielded, to provide control data for other colonies of bees in unshielded hives. The unshielded bees exhi- bited marked evidence of E-field-induced disruption, physiologically and behaviorally, and the degree of disruption was monotonically related to the density of the E field. Virtually no attenuation of the H field occurred in the shielded hives that housed the control bees; although in-hive measures of bees in these hives yielded little evidence of somatic or behavioral upset, there was a marked reduction in efficiency of their foraging behavior as a function of proximity to the HVTL. Densities of the H field at the various locations of control hives were not reported, but presumably were quite low because the HVTL was operating at an approximate five percent of load during the tenure of the experiment.

Lower Vertebrates

Aquatic species. As noted under observational studies, both sea and fresh-water animals of several species possess a demonstrable sensitivity to the geomagnetic field. Relatively few experiments have been reported that provide evidence bearing on sensitivity of intact fish, but findings in two reports (Brown et al., 1974, 1979) are noteworthy because they provided evidence that a specialized receptor system in sharks, skates, and rays--the ampullae of Lorenzini--is sensitive alike to weak, time-varying E and H fields, the latter at rms densities well below the geomagnetic mean. We note, too, that H-field reception by the ampullae is not mediated by ferrimagnetic domains but by another, as yet unclarified, mechanism.

Higher Vertebrates

Avian species. Controversy long surrounded the question of H-field sensitivity by the homing pigeon after Yeagley (1974) proposed the magnetic-homing hypothesis. A series of negative reports (Orgel and Smith, 1954; Meyer and Lambe, 1966; Emlen, 1970; Beaugrand, 1976; Kreithen and Keeton, 1974) interspersed with positive reports (Reille, 1968; Bookman, 1977; and Emlen, 1977) has resolved one question while leaving another unanswered. Magnetic homing by some pigeons does occur under controlled conditions in a natural setting (Gould, 1980), but the dependence on the geomagnetic field is contingent because the field is a second option. A primary cue for homing is position of the sun, and only when solar cues are precluded by overcast skies does a procedure based on HMI (magnetic-field interference) disrupt homing behavior. That is, DC H field produced by small, permanently magnetized bars or by energized coils fastened to the birds' heads selectively disrupted homing behavior during periods of overcast, but not during presence of the sun (cf. Emlen, 1977; Gould, 1980). Nonmagnetic bars or nonenergized coils did not disrupt the pigeons' homing behavior.

The unresolved question relates to the frequent lack of success in attempts to demonstrate sensitivity to H fields by the pigeon in the laboratory. Bookman (1977) reported findings that may hold the key to successful confirmation. Pigeons in a T-maze were rewarded with food if they correctly discriminated which of two limbs of the maze contained a food hopper. The empty limb was magneticallly shielded; the limb containing the hopper was located in an H field at an rms density of 0.05 mT. Apparently, the birds were able to differentiate the limbs by using the H field as a cue. Successful discrimination of the field was strongly associated, however, with "fluttering" behavior at the choice point. Unless a bird fluttered its wings before making its choice, successive discriminations of the correct limb fell to chance levels. Bookman interpreted this datum as an indication that motor activity by the bird is a prerequisite for detection. On physical grounds, dithering movements of body parts would permit magnetic lines of force to intercept and induce a current in a conductive medium. No energy would be coupled from a DC H field to a conductive medium in the absence of relative motion.

Findings similar to those of Bookman were reported for the domestic chicken (Clarke and Justesen, 1979). Individual roosters in a solenoid that was excited by a DC or 60-Hz current were observed for detection of fields that respectively averaged 4.0 and 1.7 mT. The highly sensitive technique of conditional suppression (Estes and Skinner, 1941)--a procedure combining operant and Pavlovian conditioning--was used as the measure of detectability. First a bird was trained to peck at a key for reinforcers of grain. When the operant pecking response had stabilized at a high rate, formal trials began. Aperiodically, the solenoid was energized for a 90-s period; and then, coincident with inactivation of the field, a brief but intense electric shock was administered to the feet of a bird. Suppression of operant responding occurred frequently during activation of the field, which is the criterion of detection, but the birds also frequently attempted to escape from the solenoid during application of the field. Flapping of the wings was rapid and forceful during the attempts to escape, as was movement of the head, which produced large numbers of spurious depressions of the operant pecking key. Given a conditional response that mixed inhibition of behavior (total immobilization) with bouts of attempted flight, the authors analyzed the variances of the birds' operant data and found highly reliable differences between control periods (no field) and periods of H-field exposure.

Although evidence of detection was stronger for the 60-Hz than for the DC field, the variances derived from periods of exposure to the DC field reliably exceeded those from control periods. Quite possibly, the rapid, jerky movements of the head permitted detection of the field by enabling transfer of energy. It is evident, in any event, that the label "DC" was only nominal, because the animal's behavior introduced a time-varying characteristic to the internal field.

Mammals

Murine species. Altered motor, operant, or exploratory activity of rats that were exposed to a sinusoidal H field at 0.5 Hz and at densities of 0.3 to 3.0 mT was reported in a series of papers by Persinger and colleagues. Common to each of the reports was assessment of behavior after a prolonged period (4 to 30 days) of continuous exposure to the field of a rotating magnet. In two of the studies (Persinger, 1969; Persinger and Foster, 1970), rates exposed *in utero* were observed as young adults for open-field activity, and for aversion of electric shock, under both conditions, behavior was reliably depressed relative to that of controls. In a third study (Persinger and Pear, 1972), young adults exposed *in utero*, as before, exhibited more sensitivity to a conditional sensory stimulus that heralded intense stimulation by electric shock than did controls. And in a fourth study (Persinger et al., 1972), rats exposed as adults for 21 to 30 days under the same field conditions exhibited increased exploratory activity relative to activity of controls. In sum, the data from the studies of Persinger and colleagues are consistent with the interpretation that exposure of the rats to the weak H field, whether *in utero* or as young adults, resulted in enhanced sensitivity to benign or painful stimuli, which is indicative of hyperemotionality.

Independent attempts to confirm the *in-utero*-related findings of Persinger and colleagues on rats have not been reported to date, but behavioral studies of murine species exposed to H fields as adults have been reported by us (Smith and Jusatesen, 1977) and by Davis et al. (1984). In our studies, a total of 39 mice was exposed in social groups of three animals per group to a 60-Hz field at a mean density of 1.7 mT. Gross motor activity was the end point. Exposure of mice of several groups (5 sets DBA, 8 sets of the CD-1 strain) occurred intermittently during a 48-h period. Approximately 150 six-minute measures of activity were recorded aperiodically, the first and last two minutes of each measure in the absence of the field; the central two minutes, during activation of the field. This procedure permitted each group of mice to serve as its own control: The first two minutes of each period provided a control baseline of activity; the second two minutes, a measure of activity *in* the field; and the third two minutes, a measure of carryover. Means of activity counts of both strains of mice were invariably higher during periods of exposure than during the baseline periods, but there was no evidence of carryover. That is, the increases of motor activity were time-locked to the presence of the 60-Hz field.

In the study of Davis et al (1984), mice in groups of seven were continuously exposed for 72 h to a 60-Hz field at a density of 1.65 mT. The investigators found no reliable differences between open-field exploratory behavior of exposed mice and that of sham-exposed controls, which led them to conclude that their results differed from those of other investigators that had reported behavioral changes at comparable densities. Although the reports of these investigators were not cited by Davis et al., the similarity of their field parameters to those used by us invites comment. At least 10 procedural differences distinguished their work from ours, any 1 or more of which could account for a difference in outcomes. But in point of fact, when the only end point common to both experiments is compared-=-Davis et al. observed open-field activity after the 72-h exposure--their finding of a null difference comports fully with our findings of no carryover: The increases of activity observed in our mice were time-locked to the field.

Recently completed experiments by Thomas et al. (1985) have revealed evidence that the rat's operant timing behavior is disrupted by a weak 60-Hz H field, but only under conditions in which the time-varying H field is accompanied by a static H field. Control experiments with each of five rats indicated that exposure to a 60-Hz field at 0.04 mT rms, or to a DC field at 0.026 mT, had no effect on timing behavior, but when both fields were applied simultaneously, timing was disrupted. The density of the static field was critical to the demonstration of disrupted timing. At 0.04 mT, which was the density of the ambient H field in the investigators' laboratory, timing was unaffected. Only when it was reduced to 0.026 mT, which is near the mean density of the horizontal geomagnetic field in many areas of the United States, was timing affected.*

Infrahuman primates. Behavioral sensitivity by the rhesus monkey to a relatively weak H field (0.1 mT rms, 9 to 500 pulses/s) was reported by Delgado et al (1983). A solenoid located just above an animal's head was activated for 1 to 2 h, during which time a continuous film recording of an animal was made. In contrast to monkeys that were observed under an inactive solenoid, which animals remained awake but quiescent, some

*The behavioral evidence of a dual dependence of biological sensitivity on a combination of DC (geomagnetic) and AC (60-Hz) H fields is not singular; Blackman et al. (1985) recently observed that enhanced efflux of calcium ions from in-vitro brain materials exhibits a similar dependence. Perhaps related also are findings by Delgado and colleagues (Delgado et al., 1982; Ubeda, et al., 1983). An increased incidence of malformations was observed in chick embryos that had been exposed during incubation to pulsed H fields at rms-microtesla densities. Investigators in the United States have been unable to confirm the embryotoxic datum (Tell et al., 1984), but there is evidence that the density of the geomagnetic field in Prof. Delgado's laboratory, circa 0.034 mT, differs from that in the laboratory that yielded negative findings (Tell and Berman, 1984). The possibility that the geomagnetic field contributed to the avian fetotoxicity is speculative; but the nature of the finding is such that attempts to confirm it or to isolate source(s) of artifact are imperative.

monkeys appeared to be narcotized while others exhibited symptoms of hyperexcitability, depending on pulse parameters. An extensive series of experiments performed on the same species by de Lorge (1984) yielded no evidence of behavioral sensitivity. Sinusoidal fields ranging from 10 to 75 Hz in frequency and from 0.8 to 1.0 mT rms in density were applied 2 to 8 h per day a total of 4 to 13 times. The end points assessed were motor activity, reaction time, and simple and complex operant behaviors. Taken together, the date of Delgado's group and the date of de Lorge indicate that the short rise times or high peak densities of the pulsed field used by the former investigators may be necessary to provoke a behavioral reaction from the monkey. Consistent with this interpretation are data from Delgado's laboratories (cf. Delgado et al., 1982; Ubeda et al., 1983): H Fields that approached a sinusoidal waveform did not produce adverse evidence of biological reactivity.

Human beings. Production of visual sensations--phosphenes--is associated with exposure to relatively intense H fields. A large number of independent investigations has confirmed this phenomenon (see the review by Tenforde in the present volume). Representative of the data from these investigations are findings from Sweden (Lovsund et al., 1979), which indicate that the threshold for eliciting phosphenes is frequency dependent, reaching a minimum near 20 Hz at rms densities near 10 mT. The threshold is also dependent on the adaptive state of the retina; unless dark-adapted, the threshold rises to rms densities near 20 mT.

Reports of human sensitivity to H fields at relatively low densities are clouded by conflicting outcomes. A positive report of increased reaction time (Freidman et al., 1967) to H fields at 0.1 to 0.2 Hz and at 0.5 to 1.1 mT rms is counter to negative reports by Beischer and colleagues (see Tenforde, 1985) and by Tucker and Schmitt (1978). As the data of Beischer et al. are based on a higher frequency (45 Hz) and a lower H-field density (0.1 mT rms), conclusions of generality may not be drawn. The studies of Tucker and Schmitt warrant particular scrutiny, because they represent the most rigorous attempt to date to control for spurious sensory cues.

A total of 200 human subjects was screened for ability to detect a 60-Hz H field as incident on the whole body at 1.06 mT rms and on the head at 2.12 mT rms. From this population emerged a subset of subjects that appeared to detect the field. Concerned that the subjects were responding to weak sonic or vibratory cues, the investigators assembled a special chamber and otherwise effected changes of procedure and instrumentation by which to control for sensory artifact. Repeatedly, as the investigators instituted these controls, the same subset of subjects was retested. Eventually, discriminatory performances of the erstwhile sensitive subjects fell to chance levels, which led the authors to conclude that the H field at the parameters they used is lacking as a sensory stimulus.

Although the data of Tucker and Schmitt have been widely cited as evidence against sensory discriminability of time-varying H fields circa 1 to 2 mT rms, a caveat is in order. There is no mention in their paper whether their subjects were informed of or were otherwise knowledgeable about the basis for repetitive testing, i.e., to eliminate artifact. In the light of the extensive research (e.g., Milgram, 1974) on the demand characteristics of the human-experimentation environment, which has revealed that most human beings are eager to conform to the wishes of the authority-figure (investigator), it is possible--especially with subjects selected for their sensitivity to environmental events--that the subjects perceived and responded to a demand to become insensitive. The argument on demand characteristics does not infirm the findings of Tucker and Schmitt, but it will limit their acceptance by the behaviorally sophisticated scientist until the care that was devoted to control of the physical environment is joined in experimentation with commensurate control of the social environment.

OBSERVATIONAL STUDIES

Sunspots and Influenza

The oldest and still continuing observational study that links magnetic fields to the human condition had its formal inception in 1609. In this year, the telescope and scientific curiosity were united to provide systematic observation and recording of the sun's topography. Sunspots, relatively opaque inclusions in the solar orb, are now known to be related to the changing character of the sun's magnetic field. Two centuries of observation of the roughly 22-yr cycle of waxing and waning of the number of sunspots--the polarity of the heliomagnetic field reverses on average every 11 yr--eventually confirmed suspicions of antiquity. The sunspot cycle is correlated with pandemics of flu, whence the etymology of influenza: "The disease influenced by the stars" (Webster, 1964). All but 1 of 10 recorded pandemics of influenza have occurred near a peak of sunspot activity (Ing, 1978). After the early 1930s, when typing of viral species came into medical vogue, it was discovered that a sizeable correlation exists between the sunspot peaks and appearance of mutant species of the influenza virus (Hope-Simpson, 1978).

Correlation versus Causation: The Solar Connection

The causal nexus that links sunspots, mutations, and influenza is unknown--if, indeed, there is a causal linkage. We think the following chain of events may be involved: Associated with peaks of sunspot activity is an increase in the density of the "solar rain," the shower of charged particles that emanate from the sun's thermonuclear furnace. These charges in turn are associated with a deformation of the geomagnetic field, resulting in periods of unstable density. And finally, on the assumption that the geomagnetic field acts as a partial shield to mutagenic radiations, the periods of minimal shielding of the biosphere would be associated with a heightened probability of a virulent mutation. It is possible, of course, that solar-induced variations of the geomagnetic field have a more direct route of adverse biological intervention, but a testable mechanism of interaction has yet to be advanced.

Observational Analysis: Pro and Con

Observational and correlative analyses involving geomagnetic variables are time-consuming and lack causal specificity. But there is one decided virtue in the hypothesis that the geomagnetic field has nontrivial incurions on biological systems, whether direct or indirect. Data on both the time-varying and quasi-static components of the geomagnetic field are continuously monitored and recorded, as are data on, say, incidence and prevalence of viral disease. These data are truly public in the scientific sense of the word, and as such they provide an unimpeachably open basis for analyzing the past and anticipating the future in the contexts of epidemiology and case studies.

The Geomagnetic Field and Immune Competence

To the end of performing a correlative case study, we have collaborated for several years with a microbiologist, Dr. Robert Garrison, and an experimental immunologist, Dr. Moshe Shifrine, in a continuing study of geomagnetism in relation to measures of immune competence (see, e.g., Smith et al., 1983). A colony of dogs (Beagles) is maintained by Dr. Shifrine in open kennels on the campus of the University of California at Davis. Samples of blood drawn monthly are used to assay the dogs' cellmediated immune system. Whole-blood lymphocyte counts are made in consequence of mitogenic stimulation by concanavalin A (CON A) and phytohemagglutinin (PHA). The monthly counts of lymphocytes from individual dogs are then analyzed in terms of monthly-averaged numbers reflecting variations of the geomagnetic field.

Garsd and Shifrine (1982) found earlier that reactivity of the cell-mediated immune system in the Beagle reliably followed a seasonal pattern. In the search for the basis of this seasonal relationship, we (Smith et al, 1983) observed that the monthly means of variation of the geomagnetic field--based on the *aa* means and immune end points, and we also analyzed as covariates two other variables that are highly seasonal, the monthly means of temperature and of precipitation in California. These data were obtained from the National Climatic Center, Asheville,, North Carolina. The data for this analysis covered the period from August of 1977 through December of 1981, which was a period of rising, then falling, sunspot activity.

A generalized least-squares regression analysis of the deseasonalized data revealed that lymphocyte counts under challenge by both Con A and PHA were reliably correlated with variations of the geomagnetic field (Con A, $r_z = -.35$, at a 4-month lag; PHA, $r_z = -.29$, at a 6-month lag; both *P*s .001). A second, more conservative analysis for synchrony yielded similar results. Temperature and precipitation were not reliably associated with the lymphocyte end points. Validation of this observation--that cell-mediated immunity in the canine animal is associated with seasonal fluctuations of the geomagnetic field--would have obvious implications for the human population.

Clinical Application of H Fields

The passage of ionic currents via implanted electrodes across nonuniting bone fractures can promote successful healing, a clinical feat that was pioneered by Robert Becker and colleagues (cf., e.g.. Becker et al., 1964; Bassett et al., 1964; Becker et al., 1977). More recently, Andrew Bassett and colleagues have reported that nonuniting fractures and other diseases of bone such as avascular necrosis respond to pulsed, low-frequency H fields that are applied noninvasively from an external source (e.g., Bassett, et al., 1974; Bassett, 1983). The absence of detailed information or parameters of the pulsed field has precluded laboratory confirmation of salutary changes in bony tissue, but validation of such changes would have a profound impact, not only on large populations of patients, but on human understanding of the basic biophysics of field-body interactions.

CONCLUSIONS

Our synopsis of experimental and observational studies has led us to a number of conclusions. First, broadly speaking, there is much honest labor to be done in clarifying biological roles played by natural H fields as well as by those of human industrial origin.

Second, we note the emergence during the past decade of several positive findings that link H fields with alteration of biological end points; because some of these reports portend adverse outcomes, there is need for independent work to confirm or disconfirm--to establish more firmaly, or to limit further, the generality of positive findings. Third, we recognize that the available data, although characterized by many voids, tend to reflect a decreasing sensitivity to H fields on the part of more advanced species. But fourth, we note that disruption of any link in the ecological chain has the potential to affect adversely other species, including the human being. And finally, fifth, there is a distinctly positive aspect to a perfection of knowledge of H-field interactions with the human body: Enhanced diagnosis, prevention, and treatment of disease.

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ROLE OF FEDERAL AGENCIES IN ELECTROMAGNETIC FIELD EFFECTS

ENVIRONMENTAL PROTECTION AGENCY

Richard D. Phillips

"THE ADMINISTRATION SHALL ADVISE THE PRESIDENT WITH RESPECT TO RADIATION MATTERS, DIRECTLY OR INDIRECTLY AFFECTING HEALTH, INCLUDING GUIDANCE FOR ALL FEDERAL AGENCIES IN THE FORMULATION OF RADIATION STANDARDS..."

FIGURE 1 Rationale for EPA interest in nonionizing radiation.

THE REORGANIZATION PLAN TRANSFERRED CERTAIN REGULATORY AND RESEARCH RESPONSIBILITIES OF THE BUREAU OF RADIOLOGICAL HEALTH. THESE TRANSFERRED COMPONENTS BECAME THE NUCLEUS FOR THE STAFF AND DUTIES OF THE EPA RADIOFREQUENCY RADIATION HEALTH EFFECTS RESEARCH PROGRAM IN THE OFFICE OF RESEARCH AND DEVELOPMENT (ORD) AND THE REGULATORY FUNCTIONS IN THE OFFICE OF RADIATION PROGRAMS (ORP).

FIGURE 2

AGENCY POLICY HAS DETERMINED THAT THE AUTHORITY TO DEVELOP FEDERAL GUIDANCE FOR RADIATION EXTENDS TO BOTH IONIZING AND NONIONIZING RADIATIONS. GUIDANCE WOULD APPLY TO FEDERAL AGENCIES WITH SPECIFIC RESPONSIBILITIES FOR RADIATION APPLICATIONS AND CONTROL. THE DEVELOPMENT OF SPECIFIC STANDARDS AND ENFORCEMENT IS THE RESPONSIBILITY OF THE IMPLEMENTING AGENCIES.

FIGURE 3

OFFICE OF RESEARCH AND DEVELOPMENT (ORD):
HEALTH EFFECTS RESEARCH

OFFICE OF RADIATION PROGRAMS (ORP):
REGULATIONS AND ENVIRONMENTAL MONITORING

FIGURE 4 EPA organization.

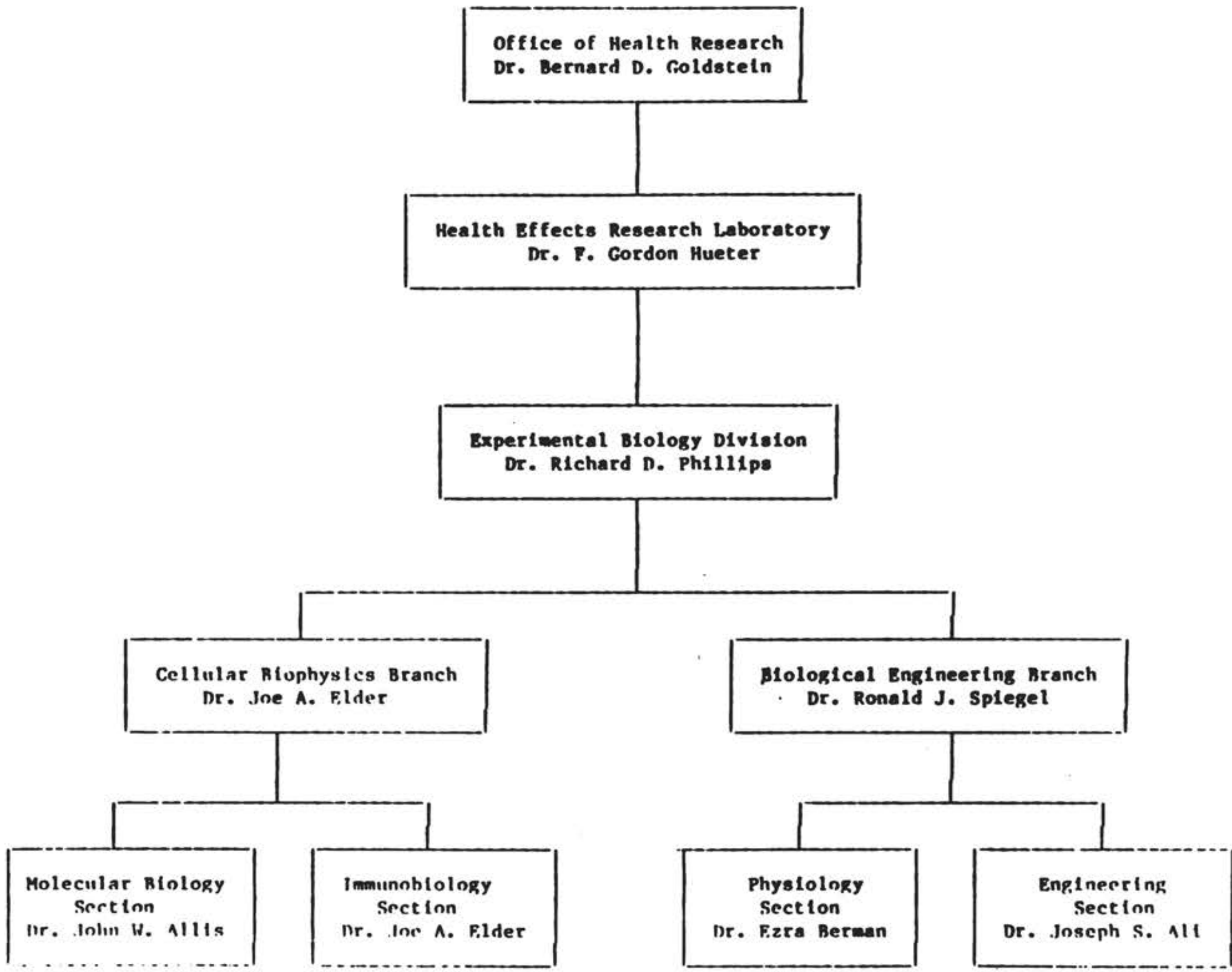
Office of Health Research
Dr. Bernard D. Goldstein
Health Effects Research Laboratory
Dr. F. Gordon Hueter
Experimental Biology Division
Dr. Richard D. Phillips
Cellular Biophysics Branch
Dr. Joe A. Elder
Biological Engineering Branch
Dr. Ronald J. Spiegel
Molecular Biology Section
Dr. John W. Allis
Immunobiology Section
Dr. Joe A. Elder
Physiology Section
Dr. Ezra Berman
Engineering Section
Dr. Joseph S. Ali

FIGURE 5

CONSOLIDATED IN THE HEALTH EFECTS RESEARCH LABORATORY AT RESEARCH TRIANGLE PARK, NORTH CAROLINA.

LARGEST INTRAMURAL HEALTH EFFECTS RESEARCH PROGRAM IN THE U.S.

FIGURE 6 Health Effects Research Program.

EXPERIMENTAL BIOLOGY DIVISION

Richard D. Phillips, Director
Teresa D. Wall, Secretary
Lonnetta K. Williams (SIS)

Cellular Biophysics Branch

*Joe A. Elder, Chief
Nancy C. Sawaya (PPT), Secretary

Molecular Biology Section

*John W. Allis, Chief
Barbara S. Robinson
John Foster (T)
*Carl F. Blackman
Shawnee G. Benane
Maureen M. Pollock (PPT)
Linda S. Kinney (Co-op)
*Kirk T. Kitchin
Victoria L. O'Brien (SIS)
*Thomas R. Ward

Immunobiology Section

Joe A. Elder, Act. Chief
*Charles G. Liddle
Julia P. Putnam

Biological Engineering Branch

*Ronald J. Spiegel, Chief
Barbara C. Crabtree (PPT), Secretary

Physiology Section

*Ezra Berman, Chief
Ora H. Lewter
Hershell B. Carter
*Christopher J. Gordon
Merritt D. Long
Kimi S. Fehlner (T)
*William P. Watkinson
Vacancy

Engineering Section

*Joe S. Ali, Act. Chief
*Joseph F. Peoples
*James B. Kinn
*William T. Joines (T)
Vacancy

*Principal Investigators (10 PhD, 2 DVM, 2 MS, 1 BS)

PPT - Permanent Part-Time
T - Temporary
SIS - Stay-in-School Student
Co-op - Student Co-op Program

Contract Support Personnel

E. Baker Bailey, elec. tech. (project supervisor)
Dottie Elliott, programmer associate
Mohammed Fatmi, electrical engineer senior
Paul Killough, mechanial engineer senior
Diane Miller, project scientist
Earl Puckett, lab analysis
Charles Summey, associate engineer

FIGURE 7

- Electrical Engineering
- Microwave Engineering
- Physics
- Physical Chemistry
- Biophysics
- Biochemistry
- Immunology
- Thermal Physiology
- Experimental Psychology
- Teratology
- Behavior
- Neurobiology

FIGURE 8 Research disciplines.

RESOURCE SUMMARY (MAN-YEARS)	
1976	25
1977	25
1978	25
1979	28
1980	28
1981	28
1982	25
1983	16
1984	16
1985	16

RESOURCE SUMMARY ($ MILLIONS)	
1976	770,000
1977	960,000
1978	830,000
1979	1,880,000
1980	2,770,000
1981	1,910,000
1982	2,310,000
1983	1,360,000
1984	560,000
1985	930,000

FIGURE 9

<u>RADIOFREQUENCIES</u>

NEUROLOGICAL STUDIES

LONG-TERM LOW-LEVEL EXPOSURE

DOSE/EXTRAPOLATION MODELING

THERMOREGULATION

<u>EXTREMELY LOW FREQUENCIES</u>

MECHANISMS

DEVELOPMENT

NEUROLOGICAL

DRUG INTERACTIONS

FIGURE 10 Major areas of research (1985).

ORP (REGULATIONS) ⇌ ORD (RESEARCH)

GUIDANCE UNDER DEVELOPMENT BY ORP WILL NOT ADDRESS SUCH IMPORTANT AREAS AS:

CHRONIC, LOW-LEVEL EXPOSURE
POPULATION SENSITIVITY
MODULATION
INHOMOGENEOUS ABSORPTION
FREQUENCY-SPECIFIC EFFECTS
MECHANISMS

RESEARCH IN THESE AREAS NEEDS TO BEGIN NOW SO THAT THESE ISSUES CAN BE ADDRESSED IN A MAJOR REVISION OF THE HEALTH EFFECTS DOCUMENT IN SUPPORT OF THE AGENCY'S REEVALUATION OF THE RF RADIATION GUIDANCE IN FY 89.

FIGURE 11 RF radiation research needs.

"WE DO NOT PERCEIVE THAT THE ISSUANCE OF GUIDANCE FOR RADIOFREQUENCIES IN FY 85 WILL REDUCE THE SUPPORT WE NEED FROM ORD TO MAKE REGULATORY DECISIONS AT HIGHER AND LOWER FREQUENCIES OR TO REEVALUATE GUIDANCE FOR ISSUANCE IN FY 89. THE HEALTH EFFECTS RESEARCH STAFF IS THE ONLY SOURCE OF SUPPORT WE HAVE TRACKING AND EVALUATING RESEARCH RESULTS AND FOR CONDUCTING AN INTEGRATED (INTRAMURAL AND EXTRAMURAL) RESEARCH PROGRAM TO RESOLVE IMPORTANT ISSUES.

FIGURE 12

RADIOFREQUENCIES

Carcinogenesis (Szmigielski, Guy)

Drug Interactions (Thomas)

Modulation (Adey, Bawin, Blackman)

Immunology (Czerski)

Dose/Extrapolation Modeling (Guy, Spiegel, Gandhi)

Brain Morphology (Hansson)

EXTREMELY LOW FREQUENCIES

Carcinogenesis (Wertheimer, Hamnerius, Milham)

Fetal Development (Delgado, Mild, Sikov, Nordstrom)

Central Nervous System (Hannson)

Circadian Rhythm (Semms, Wilson, Ehret)

Behavior (Lovely, Sagan, Stern)

Membrane Interactions (Adey, Blackman)

Dose-Response Data

Dosimetry/Modeling

Mechanisms

FIGURE 13 Research needs.

- **Increased Emphasis on Extremely Low Frequencies**

  Carcinogenesis

  Fetal Development

  Behavior

  Mechanisms

  Dosimetry

- **Radiofrequencies**

  Life-Span Study

  Epidemiological Study

  Carcinogenesis

  Dose/Extrapolation Modeling

  Behavior

FIGURE 14 EBD FY 86 research plans (if program is funded).

U.S. DEPARTMENT OF ENERGY
OFFICE OF HEALTH AND ENVIRONMENTAL RESEARCH

Martin L. Minthorne, Jr.

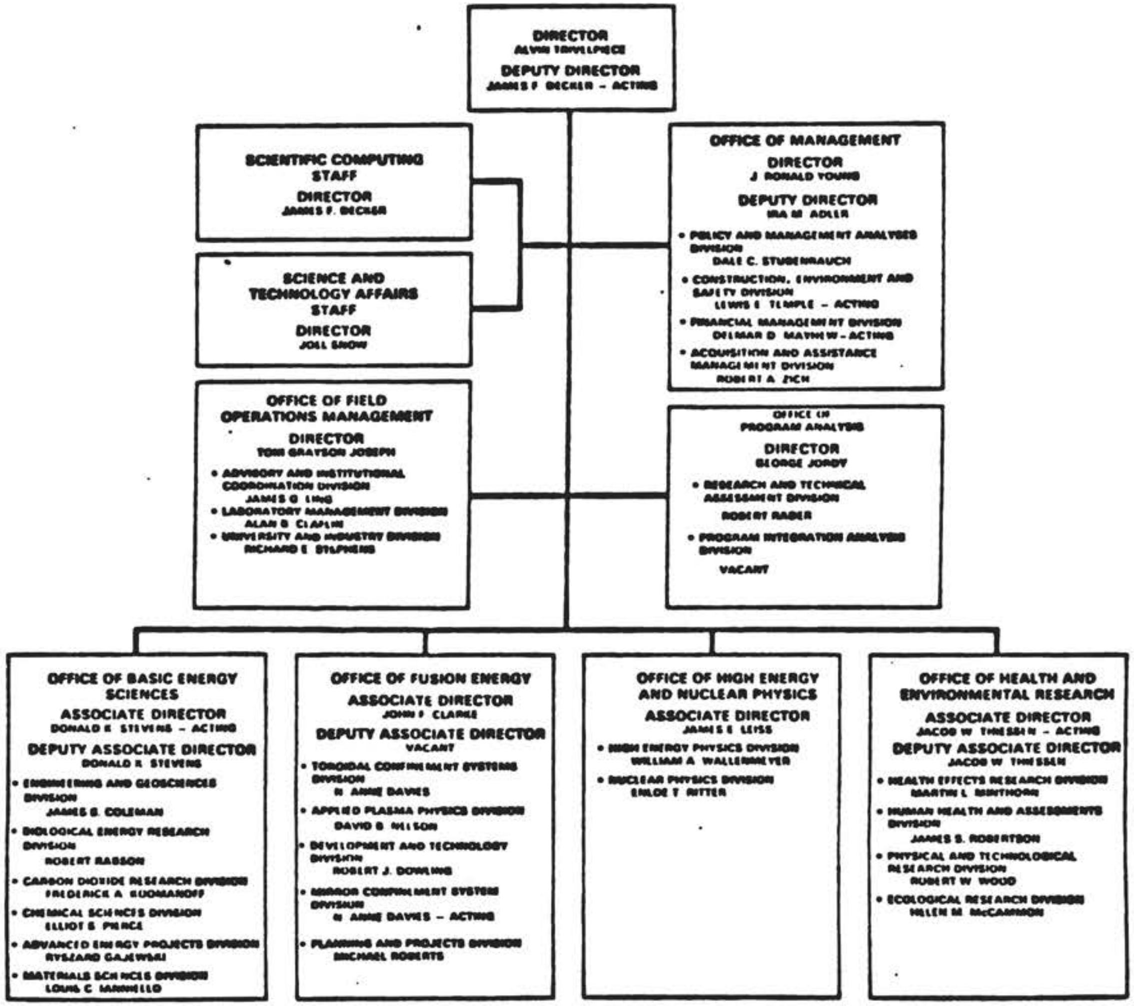

FIGURE 1 Office of Energy Research.

- **PROVIDE SCIENTIFIC DATA AND UNDERSTANDING TO REDUCE HEALTH AND ENVIRONMENTAL UNCERTAINTIES ASSOCIATED WITH PROMISING ENERGY TECHNOLOGIES NEEDED TO MEET THE NATION'S FUTURE ENERGY AND NATIONAL SECURITY REQUIREMENTS**

- **PROVIDE NEW APPLICATIONS OF NUCLEAR TECHNOLOGIES TO IMPROVE THE DIAGNOSIS AND TREATMENT OF HUMAN DISEASE**

FIGURE 2 Office of Health and Environmental Research: Program Goals.

- IDENTIFY POTENTIALLY HAZARDOUS ENERGY-RELATED AGENTS SUBJECT TO ENVIRONMENTAL RELEASE

- ELUCIDATE THE TRANSPORT AND FATE OF THESE AGENTS IN THE ENVIRONMENT

- DETERMINE THEIR ECOLOGICAL IMPACTS AND ENVIRONMENTAL PATHWAYS TO HUMANS

- QUANTIFY ENERGY-ASSOCIATED RISKS TO HUMAN HEALTH BY DIRECT OBSERVATIONS THROUGH BASIC AND APPLIED RESEARCH

- DEVELOP NEW AND IMPROVED MEDICAL APPLICATIONS OF RADIATION AND ISOTOPES

FIGURE 3 Office of Health and Environmental Research: Program Objectives.

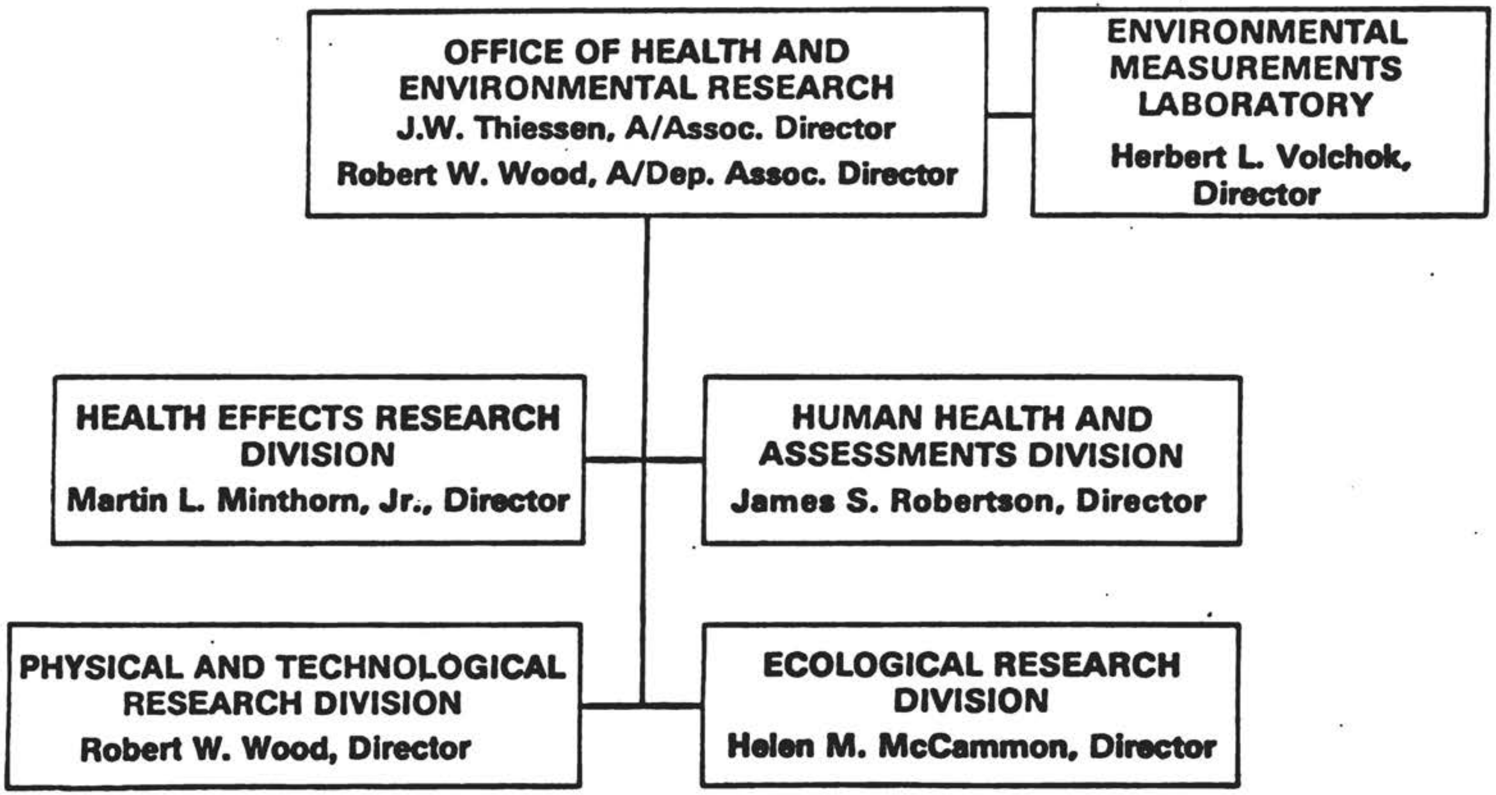

FIGURE 4 Office of Health and Environmental Research: Organizational Chart.

HUMAN HEALTH AND ASSESSMENTS	HEALTH EFFECTS RESEARCH	ECOLOGICAL RESEARCH	PHYSICAL AND TECHNOLOGICAL RESEARCH
HUMAN HEALTH EFFECTS FROM ENERGY GENERATION	CARCINOGENESIS	TRANSPORT AND CONVERSION OF ENERGY-RELATED POLLUTANTS IN TERRESTRIAL & AQUATIC ECOSYSTEMS	ANALYTICAL CHARACTERIZATION
OCCUPATIONAL HEALTH AND MEDICAL RESEARCH	MUTAGENESIS	EFFECTS OF ENERGY-RELATED PROCESSES AND POLLUTANTS	ATMOSPHERIC TRANSPORT AND TRANSFORMATION
BIOMEDICAL APPLICATIONS	SYSTEMS DAMAGE (TOXICOLOGY)	FUNDAMENTAL ENVIRONMENTAL PROCESSES	PHYSICS & CHEMISTRY OF POLLUTANT INTERACTIONS
	GENERAL LIFE SCIENCES		MEASUREMENT SCIENCE
			OCCUPATIONAL HEALTH AND SAFETY

FIGURE 5 Office of Health and Environmental Research: Program Organization.

	FY 1983	FY 1984	FY 1985
HUMAN HEALTH RESEARCH	$ 25,110	$ 25,567	$ 24,755
HEALTH EFFECTS RESEARCH IN BIOLOGICAL SYSTEMS	56,683	57,004	59,503
ENVIRONMENTAL RESEARCH	25,285	23,746	21,322
PHYSICAL AND TECHNOLOGICAL RESEARCH	28,851	27,612	35,406
HEALTH AND ENVIRONMENTAL RISK ANALYSIS	1,780	1,806	0
NUCLEAR MEDICINE APPLICATIONS	18,463	20,826	21,792
PROGRAM DIRECTION	3,350	3,313	3,450
TOTAL OPERATING EXPENSES	159,522	159,874	166,228
CAPITAL EQUIPMENT	12,877	8,300	7,936
CONSTRUCTION	3,100	2,400	3,000
TOTAL OHER	$175,499	$170,574	$177,164

FIGURE 6 Office of Energy Research. Health and environmental research (budget in thousands).

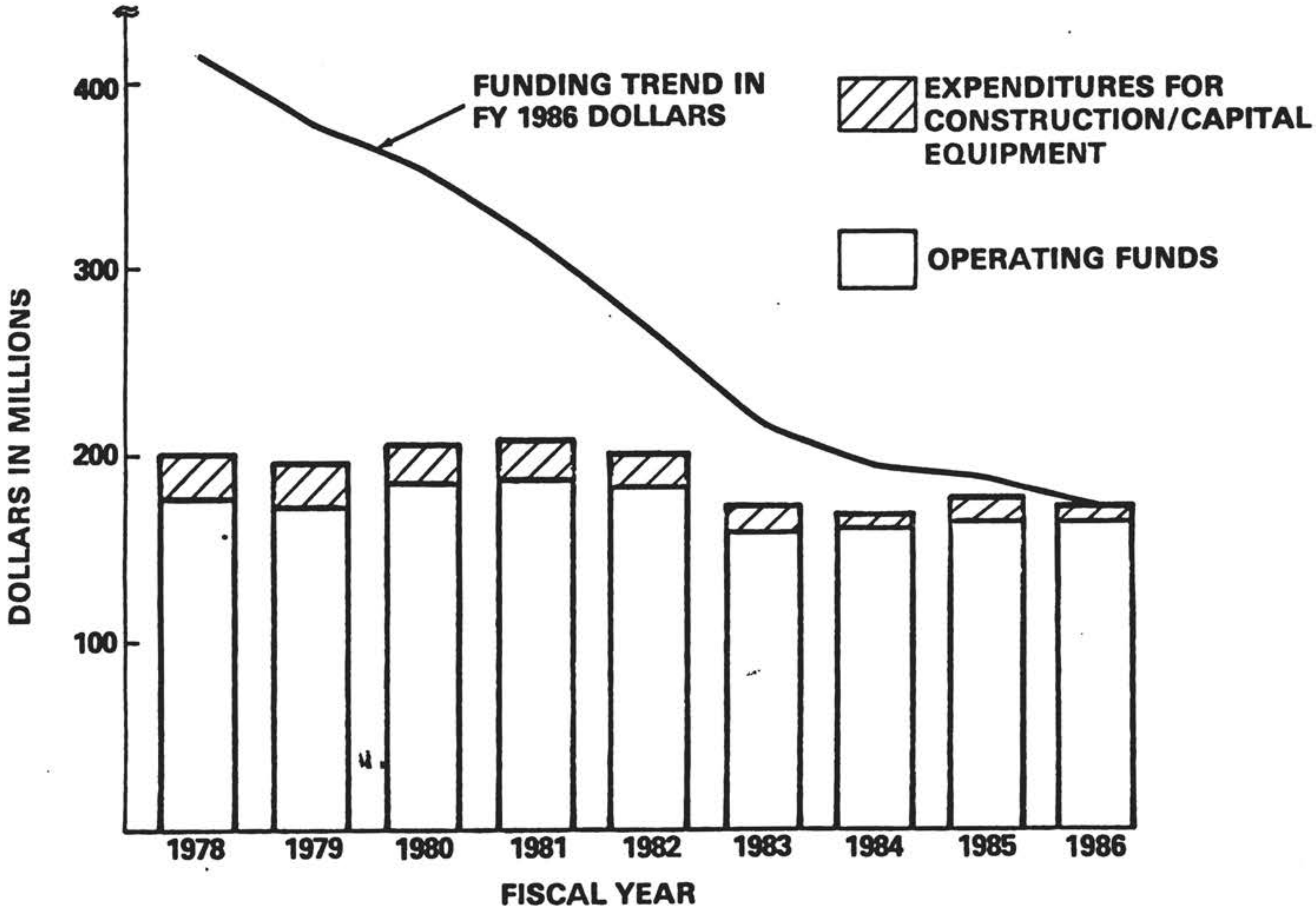

FIGURE 7 Health and environmental research. Recent funding pattern.

AEC PERIOD (1946 — 1975)

- SPECIAL, LONG-TERM COMMITMENT TO THE DEVELOPMENT OF NUCLEAR ENERGY
- ESTABLISHMENT OF NATIONAL PROGRAM OF RESEARCH ON HEALTH AND ENVIRONMENTAL ASPECTS OF NUCLEAR POWER PRODUCTION AND USE

ERDA PERIOD (1975 — 1977)

- EMPHASIS ON DEVELOPMENT OF ADVANCED NON-NUCLEAR ENERGY TECHNOLOGIES
- ESTABLISHMENT OF MAJOR PROGRAMS OF RESEARCH ON HEALTH AND ENVIRONMENTAL ASPECTS OF NON-NUCLEAR ENERGY TECHNOLOGIES

FIGURE 8 Office of Health and Environmental Research: Historical Perspective.

DOE PERIOD (1977 — 1981)

- CLOSE COORDINATION OF HEALTH AND ENVIRONMENTAL RESEARCH WITH ENERGY TECHNOLOGY RESEARCH AND DEVELOPMENT
- EMPHASIS ON PROCESS-SPECIFIC HEALTH AND ENVIRONMENTAL RESEARCH AND ON SHORT-TERM BIOLOGICAL TESTING AND CHEMICAL CHARACTERIZATION

DOE PERIOD (1981 — PRESENT)

- PROCESS-SPECIFIC RESEARCH TERMINATED
- EMPHASIS ON LONG-TERM GENERIC AND BASIC RESEARCH (ANTICIPATORY RESEARCH)
- DECREASED EMPHASIS ON NON-NUCLEAR RESEARCH PROGRAMS
- REDUCED FUNDING FOR HEALTH AND ENVIRONMENTAL RESEARCH

FIGURE 8 - Continued

GEOTHERMAL ENERGY SYSTEMS

- HYDROTHERMAL
- HOT, DRY ROCK

SOLAR ENERGY SYSTEMS

- PHOTOVOLTAICS
- SOLAR THERMAL
- HEATING AND COOLING (BUILDINGS)
- BIOMASS FUELS
- LOW-HEAD HYDROELECTRIC
- OCEAN THERMAL ENERGY CONVERSION

FOSSIL ENERGY SYSTEMS

- FLUIDIZED BED COMBUSTION
- COAL GASIFICATION
- COAL LIQUEFACTION
- OIL SHALE
- MAGNETOHYDRODYNAMICS

ENERGY CONSERVATION SYSTEMS

- ALTERNATE AUTOMOTIVE FUELS
- ELECTRIC STORAGE BATTERIES
- ELECTRIC POWER TRANSMISSION
- RANKINE BOTTOMING CYCLES
- ENERGY EFFICIENCY IN BUILDINGS

FIGURE 9 Office of Health and Environmental Research. Principal areas of nonnuclear energy research, 1987-1980.

	FY 1981	FY 1982	FY 1983	FY 1984	FY 1985	FY 1986
FISSION (NUCLEAR)	55,569	60,054	54,695	56,567	52,628	53,149
FUSION (NUCLEAR)	1,454	1,577	1,081	1,186	849	919
FOSSIL ENERGY	47,948	46,134	23,392	19,804	18,483	16,526
OTHER NON-NUCLEAR	8,881	7,453	3,288	1,874	722	565
MULTITECHNOLOGY	20,925	23,702	39,345	37,207	43,399	41,784
GENERAL LIFE SCIENCES	24,000	26,400	19,258	22,410	28,355	28,051
NUCLEAR MEDICINE	17,440	18,986	18,463	20,826	21,792	21,226
FACILITY OPERATIONS	20,000	15,700	15,977	10,700	10,936	11,000
TOTAL OHER	196,217	200,006	175,499	170,574	177,164	173,220

FIGURE 10 Office of Health and Environmental Research. Energy technology support (budget in thousands).

OFFICE OF HEALTH AND ENVIRONMENTAL RESEARCH

ROLE IN THE SPONSORSHIP OF RESEARCH ON BIOLOGICAL EFFECTS OF ELECTROMAGNETIC FIELDS

RESEARCH ON EXTREMELY LOW FREQUENCY (ELF) FIELDS

- **ANIMAL STUDIES**
  - BEHAVIOR; PERCEPTION OF FIELDS
  - NEUROENDOCRINE RESPONSES
  - REPRODUCTIVE EFFECTS
  - GENETIC EFFECTS
  - NERVE FUNCTION
- **CELL STUDIES**
  - CELL VIABILITY
  - REPLICATION AND GROWTH
  - DNA DAMAGE; GENETIC EFFECTS
  - MEMBRANE FUNCTION
  - CELL SURFACE DYNAMICS
- **DOSIMETRY STUDIES**
  - DOSE MEASUREMENTS
  - INTERSPECIES SCALING OF DOSE
- **SUPPORT OF NEW YORK STATE POWERLINES PROJECT**

FIGURE 11 Office of Health and Environmental Research. Research on biological effects of electromagnetic fields. Scope of the program.

RESEARCH ON DC MAGNETIC FIELDS

- EPIDEMIOLOGY STUDY
- ANIMAL STUDIES
  - PHYSIOLOGICAL RESPONSES; CIRCADIAN RHYTHMS
  - GENETIC EFFECTS
  - BIOLOGICAL DEVELOPMENT
  - RETINAL RESPONSES
  - CARDIAC RESPONSES
  - NERVE RESPONSES
- PLANT STUDY
  - GENETIC EFFECTS
- DEVELOPMENT AND TESTING OF PERSONNEL DOSIMETERS

FIGURE 11 - Continued

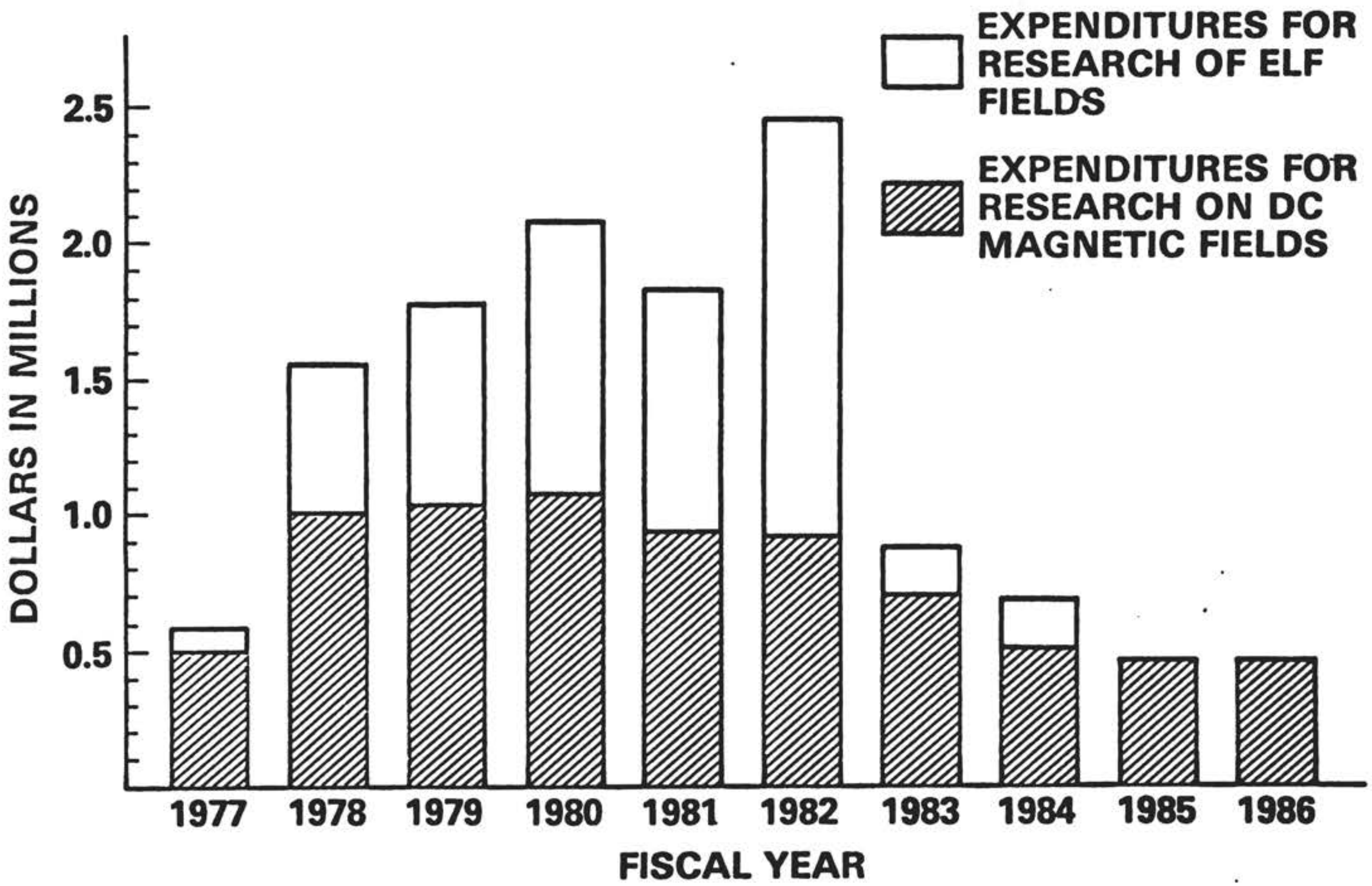

FIGURE 12 Office of Health and Environmental Research. Research on biological effects of electromagnetic fields. Funding history.

CURRENT RESEARCH (DC MAGNETIC FIELDS ONLY)

- FIRST LIFETIME EXPOSURE STUDY (MICE) (COMPLETION OF STUDY)
- PHYSIOLOGICAL PERFORMANCE AND CIRCADIAN VARIATIONS (COMPLETION OF STUDY)
- RETINAL ELECTROPHYSIOLOGY
- CARDIOVASCULAR ELECTRIC POTENTIALS AND RATE OF BLOOD FLOW
- MEMBRANCE ORGANIZATION AND FUNCTION (MODEL SYSTEM)

FUTURE RESEARCH

- NO MAJOR CHANGES PROJECTED
- REPEAT LIFETIME EXPOSURE STUDY (WITH LARGER NUMBER OF ANIMALS)
- COMPLETE RETINAL ELECTROPHYSIOLOGY STUDY
- CONTINUE CARDIOVASCULAR STUDY (FIELDS UP TO 9 TESLA)
- CONTINUE MEMBRANE STUDY(MODEL SYSTEM, BLOOD CELLS)
- INITIATE ELECTROENCEPHALOGRAPHIC STUDY

FIGURE 13 Office of Health and Environmental Research. Research on biological effects of electromagnetic fields.

RESEARCH ON LOW-FREQUENCY ELECTROMAGNETIC FIELDS IN THE U.S. VETERANS ADMINISTRATION

Don R. Justesen
Kansas City Veterans Administration Medical Center
Kansas City, Missouri 64128

THE RESEARCH MISSION OF THE VETERANS ADMINISTRATION

The primary mission of the United States Veterans Administration, in the words of Abraham Lincoln, is "To care for him who shall borne the battle..." In keeping with this mission, and because the veteran is a member of an aging population, a significant fraction of which has service-connected disabilities, the VA's basic and biomedical research programs have a two-fold emphasis: Redress of disease incident to aging, and investigations aimed at rehabilitation of individuals that have suffered combat-related trauma. Both basic and applied investigations are performed in the hundreds of medical centers that form the world's largest integrated hospital system. Virtually every scientific and biomedical discipline, from biophysics and molecular biology to electrophysiology and experimental psychiatry, is represented. Hand-in-hand with patient care and research is teaching of medical, nursing, and allied technical personnel in the larger medical centers that are affiliated with state or private schools of medicine.

STRUCTURE OF VA RESEARCH PROGRAMS

Cooperative Studies

Given its expanse, the Veterans Administration is in a unique position to perform large-scale cooperative studies, research projects in which physicians and scientists of several medical centers pool their efforts in attacking a common biomedical problem. This collective effort resulted in the 1950s in discovery of a chemotherapy for tuberculosis, which at one time accounted for occupancy of more beds than has any other disease entity in the Administration's hospital system. The savings to the taxpayer that resulted from the near-eradication of tuberculosis has more than defrayed the total investment to date in the Veterans Administration's medical research programs.

To my knowledge, none of the Veterans Administration's ongoing cooperative efforts involves research on diagnostic or therapeutic applications of electric or magnetic fields. The high incidence of arthritis and related musculo-skeletal disorders in the older veteran decidedly warrants cooperative study of the therapeutic efficacy of electric currents and magnetic fields. A former VA physician-scientist, now-retired Robert O. Becker, discovered many years ago that fractured bone, if persistently non-uniting, often will knit successfully when small electric currents are passed across the line of fracture. This maneuver requires surgical implantation of conductive electrodes into bony tissue. More recently, reports of successful union of nonuniting factures have been made for externally applied magnetic fields. This technique involves long-term, intermittent use of a time-varying magnetic field by which, presumably, an ionic current is induced to cross the line of fracture in an affected limb. Veteran patients are undergoing treatment by the magnetic modality on a contracting-out basis, but a continuing controversy about its efficacy, and the long periods in which patients are encumbered by apparatus and limited mobility, dictate the need for comparative evaluation. An approach to the noninvasive and invasive electrotherapies, by which to evaluate relative efficacy, time to cure, strength of union, differential cost, and patient comfort and mobility, would be tailor-made for cooperative study.

Individual Research Programs

The Veterans Administration also supports individual research programs of Ph.D and M.D scientists. To my knowledge, only three principal investigators (P.I.) are actively pursuing research on low-frequency electromagnetic. Electrobiologist-physician William Ross Adey, Associate Chief of Staff for Research at the Pettis Memorial Medical Center in Loma Linda, California, has pioneered with biochemist Susan Bawin the study of interactions between weak, low-frequency electric fields and nervous tissue. More recently, magnetic fields have been added to their investigative agenda. Rae Jacobs, an orthopaedic surgeon at the Kansas City Medical Center, is actively engaged in the study of efficacy and mechanisms of electric-current therapy of non-uniting fractures in canine models. I am the third P.I., having performed a modest number of studies of magnetic-field influences on behavioral and physiological end points on murine and avian models over the past ten years with my colleagues, Robert F. Smith and Rex L. Clarke.

GENERAL RESEARCH POLICY

Caveat

In the paragraphs that follow, I summarize activities and policy from the perspective of a principal investigator with a 24-year tenure in the Research Service of Veterans Administration. By way of caveat, I note that the scope of the Administration's involvement in research on low-frequency electromagnetic fields may be more extensive than that portrayed by me. A draft of this paper was provided Central Office research administrators 14 weeks before time of submission, which draft was accompanied by a written request for corrective comment. A reply was not forthcoming, the absence of which I do not construe to vouchsafe the accuracy or inclusiveness of my statements.

Recruitment of Investigators

Although understandably favoring research on problems related to the aging or disabled veteran, the policy of central office administrators regarding recruitment of individual investigators and acceptance of their programmatic interests can be characterized as impartial and laissez faire. That is, the same requirements for review of research proposals are laid to the investigator irrespective of specialty or of the color of his or her doctorate. And the worth of his or her area of research is initially judged by scientists and administrators at the medical-center level, often with the support and advice of medical-school faculty and officials. Viewed in this light, Central Office policy is not unfavorable to biomedical research involving electric and magnetic fields.

Retention of Investigators and Programs

Pursuing a career as an investigator in the Veterans Administration requires periodic reaffirmation of merit. More than a dozen merit-review panels, each of which is identified with a discrete discipline or medical specialty, and all of which are modeled after the study panels of the National Institutes of Health, provide evaluations of research proposals. Unlike the case in academe, the tenure of investigators in the Veterans Administration is contingent solely on successful review of research proposals. A principal investigator's teaching and service commitments play virtually no role in retention. If a physician's research proposal/program fails of merit review, he or she usually has the option of retaining employment as a full-time clinician. If a Ph.D. scientist fails, both loss of research support and separation from VA employment can swiftly ensue. One's status as a career civil-service employee, even as a so-called Career Research Scientist, is essentially nominal. Irrespective of years of service or past accomplishments, the basic scientist in the VA is ever dependent on "soft money."

The careers of many principal investigators and the lives of their supporting staffs have been disrupted by inactivation of their laboratories following disapproval of a proposal or receipt of an inferior priority score. Ironically, some of these scientists had been receiving joint support of their research programs by extramural grant funds for proposals that had been accorded very high priority ratings, an embarrassment for investigator and granting agency alike. Because the threat of inactivation accrues even to senior scientists with a long history of productive endeavor, the morale of most investigators in the Research Service of the Veterans Administration is dampened. The potential for loss of laboratory and livelihood hangs above like the sword of Damocles whenever the time for resubmission of a research proposal is due.

INTERDISCIPLINARY RESEARCH IN THE VETERANS ADMINISTRATION

Much Promise, Many Pitfalls

One could argue both virtue and vice in the Darwinian policy of research support by the Veterans Administration. Produce or perish are very much the watchwords. This policy has militated for selection of a cadre of productive and innovative investigators, but the outlook for the younger investigator, especially for the research-oriented physician, is not salutary. Within as well as without the VA, the neophyte investigator must complete with older, more experienced, well-established investigators for dwindling research dollars. This state of affairs has contributed to ever-decreasing numbers of the physician-scientist, who is truly a vanishing species.

For the seasoned, biomedically oriented investigator, no arena offers a more propitious opportunity for fruitful collaborative study than that of the large medical center with a diverse complement of specialists. Physicists, chemists, physiologists, and behavioral scientists often rub elbows with researching physicians in a common setting. In contrast to the typical medical school or university, in which faculties and disciplines are geographically separated and socially isolated, many medical centers in the Veterans Administration have the structure and means to provide a true multidisciplinary collegium.

Problems of Peer-Review

However great the potential for interdisciplinary endeavor in the biomedical research programs of the Veterans Administration, this potential has been and is increasingly inhibited by a flaw in the merit-review process. Obviously, the vitality of a research program is critically dependent on the validity of periodic peer-review. Given the monolithic, intradisciplinary character of the Veterans Administration's merit-review commitees, and given the sole multidisciplinary character of research that involves electric or magnetic fields and biological end points that range from molecular biology to experimental psychology, the interdisciplinary investigator is at a distinct disadvantage. No presently constituted review committee exists that embraces the requisite spectrum of specialists. Recourse may be and usually is sought to ad hoc reviewers that have the requisite expertness, but their evaluations are limited to narratives--priorities ratings are not requested--and are susceptible to misinterpretation by members of the review committee, none of whom is privy to the naunces of an exotic discipline or of the specialist's language.

A poignant instance of misinterpretation that exemplifies the disadvantage occurred a few years ago after an ad hoc review of a proposal was provided an university-affiliated engineer. The principal investigator had proposed behavioral experiments on small animals in consequence of exposing them to an electromagnetic field. In the engineer's lexicon, behavior is classed as an obserable or phenomenological construct--as opposed to the likes of quarks and electrons, which are nonobserable or inferential constructs. True to form, the engineer, although favorably disposed, characterized the proposed research as "phenomenological." A member of the merit-review committee, an individual charged to interpret the ad hoc reviewer's evaluation for the committee as a hole, construed the appellation as a highly negative criticism of the overall proposal.

Compounding the language problem are strictures on the length of research proposals. Until recently, the author of a multidisciplinary proposal had the option to compose a lengthly narrative that served a two-fold purpose: That of summarizing pertinent literatures while also providing the merit reviewer with a technical and scientific tutorial. Concision is a virtue. But a limit on the transfer of information from specialist investigator to nonspecific evaluator is an additional element of adversity that dilutes the integrity of the peer-review process.

Funding Problems

Although its peer-review process is based on the NIH model, the Veterans Administration's policy for funding individual research programs differs somewhat from that of NIH. After a merit-review committee has evaluated a proposal, which evaluation contains a consensually derived priority score and a recommended level of funding for a period of one to five years, one of three possible judgments is directed to and is generally affirmed by council: No funding of a disapproved proposal; no funding if an approved proposal has received an inferior priority score; or graded funding of an investigator whose proposal has garnered an acceptable priority score. In the case of the last-names category, a special, computer-generated "formula" is used to reduce the line of funding below that recommended by the merit-review committee. The lower the priority score, the greater the reduction in the level of obligated funding. Conjoined with a reduction of funding is a limit on the working hours of support personnel. That is, an investigator with one full-time research assistant may find a ceiling has been imposed that will require the assistant to be reduced to a 28- or 32-hour work week. This ceiling can be imposed even if the investigator has the funds to defray a full-time position.

Because an originally recommended level of funding is often well below that requested by an investigator, the second-stage reduction by fiat of computer formula constitutes a form of double jeopardy. The members of a merit-review committee are charged to determine an investigator's minimal needs consistent with prosecution of a research program. And therein lies the makings of an ethical dilemma. If the committee is aware of an ensuing reduction of support, its collective judgment is compromised--it is knowingly condoning inadequate support. If the committee is unaware, then the administrators that invoke the second-stage reduction are subverting scientific judgment.

The second-stage reductions of funding levels and personnel ceilings are not specifically targeted at the interdisciplinary investigator. They are currently mandates of policy that affect investigators of most research programs in the Veterans Administration. It is reasonable to assume, however, that the interdisciplinary investigator is the more likely to bear the adverse impacts of this policy because of a real and understandable characteristic of monolithic merit-review committees: Familiarity breeds content. A scientist is certainly more comfortable when evaluating the proposals of peers with whom he is acquainted, and of whose works he has a direct comprehension based on personal scientific experience. One is more likely to champion the familiar than the alien.

CONCLUDING COMMENTS

If my comprehension and assessment of research policy of the Veterans Administration are valid, there are formidable obstacles that face any interdisciplinary investigator affiliated with the Research Service. Foremost among the obstacles is the absence of an adequate mechanism of peer-review. This problem is not unique to the Veterans Administration and, indeed, officials of the National Institutes of Health recently have taken steps toward correction of the peer-review process.

The priority-score-contingent reductions of funding and of personnel ceilings in the research programs of the Veterans Administration have the superficial appearance of merit--should not one be serving of the most deserving?--but on closer scrutiny, a thorny ethical issue is incumbent with these practices. Either the merit-review committees or the research administrators are forced thereby to compromise scientific principle. These practices have not been invoked by officials of the National Institutes of Health, which instead have simply increased the priority-score cut-off point in funding of grants as the ratio of appropriated monies to investigators has steadily decreased.

The option of progressively elevating the cut-off point to offset the ever-diminishing funding ratio could be taken by the Veterans Administration, but beyond adoption of a relatively inferior cut-off point a few years ago, the means of coping has been a calculated and widely distributed underfunding of research programs. A delicate (and doubtless frustrating) juggling of research priorities versus morale problems has beset the research managers of the Veterans Administration. Their own ranks and support personnel have been depleted during a decade-long period in which more medical centers have been built, and morfe investigators have been seeking support. Viewed in this light, the attempts of the managers to maintain a viable Research Service are certainly borne of imposed crisis, not of mismanagement of guile.

Given the contemporary constraints on funding, and given a political climate that appears increasingly hostile to federal support of certain segments of biomedical research, the implications for support of basic or applied research on low-frequency electromagnetic fields within--or without--the Veterans Administration are hardly reassuring. In candor, I must conclude that the promise of a career as an experimental biologist is losing its luster, and all but the most courageous and brilliant among aspiring youth would be well advised to entertain other areas of endeavor.

STATEMENTS SUBMITTED TO PANELISTS

SOME REMARKS PERTAINING TO THE NRC PANEL SESSION ON APRIL 26, 1985

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GENERAL REMARKS

The Role and Scope of Government-Supported Research Policy

The government should support research that has important long-range potential and that is beyond the economic capabilities or the business policy scope of private enterprise. Priorities should be commensurate with both the degree of governmental responsibility and the importance of the research in a national context. Steadiness of government support is essential.

In general, research that is principally focused on areas that require long-term study and are crucial to the economic well-being and security of the nation and its environment is appropriate for active government support. Because of financial (particularly "bottomline") pressures, industry is rarely able to support long-range research in which the payoff may be years away. Yet the lack of such long-range perspective is a severe obstacle for effective progress of technology that is very much in the national interest.

The idea of appropriate government support of long-term research is severely compromised by extreme shifts in funding levels. A lasting commitment to research in such complex and critical areas is essential. Continuity of research is espoused by the majority, but keeping both government and industry involved in a consistent way has been difficult. Ours is not a time of instantaneous inventions and instantaneous rewards. Advancing technology requires hard, patient, and deliberate efforts for an extended period. Further, to advance technology in this modern world requires significant investment in people and capital resources. It cannot be attacked with a vengeance in one year or by one administration and abandoned totally in the following. Because of the importance of safety and reliability in electricity supply, many technologies must be demonstrated at or near commercial scale to be acceptable to the electric industry. Sharing the risk on these projects and providing funds for construction of such facilities is a particularly difficult problem when budgets change dramatically from year to year.

Finally, it is extremely important that any governmental research support policy is established with a global understanding of energy supply as a large complex system that must be viewed with a full perspective and not just in some of its details.

How the U.S. Department of Energy, Division of Electric Energy Systems (DOE-EES), and Industry's Electric Power Research Institute (EPRI) Are Complementary

In every project a certain amount of time is spent in searching for directions in which to find solutions and in generalized thinking, on a conceptual level, on the nature, scope, and context of specific possible solutions. This is a conceptual or creative phase of the project.

Also, in every project a certain amount of time is spent on producing results, i.e., working on equations, algorithms, programs, demonstrations by simulation, or experiments on equipment. This is a production phase of the project.

One could say that industry-EPRI programs are normally structured so that the conceptual phase tends to be shorter and focused more precisely. In DOE-EES-type work the conceptual phase tends to take a larger portion of the project. Also, in the Industry-EPRI type project.the production phase tends to be carried closer to immediate implementation, although all good projects should include a demonstration of the feasibility and quality of the results, at least by nontrivial simulation. Both types of projects are needed in all sizes. Also, they should be properly coordinated and detailed, as indeed they already are.

Areas of Continuing Major Conceptual Research

Areas in which the large, complex power system must vitally depend on continuing major conceptual research include:

1. eliminating vulnerabilities caused by gaps in state-of-the-art system operation and planning;
2. exploiting opportunities for upgrading system performance by more advanced and sophisticated system operation and planning methods; and
3. Creating a supply of sophisticated researchers versed in both power and system technology as needed by utilities, suppliers, and universities alike during the current age of the control center.

Let it be stated that the part of the power system in which the greatest vulnerabilities and opportunities lie is the transmission system. It is very large, complex, interacting, dynamic, and nonlinear. Its size and mathematical complexity marks the behavior and control of the transmission system, particularly in abnormal conditions, as an unusually complex and challenging problem. It will require years of very competent conceptual research to develop the most effective technology to keep it reliable and economically efficient in all circumstances.

Brief outlines of the problem complexes listed above will now be given.

Eliminating Vulnerabilities Caused by Gaps in State-of-the-Art System Operation and Planning

To understand the current degree of its vulnerability, it seems desirable to take a long-range view of the history of reliability in the power industry in the brief sketch that follows.

During the 1930s an exceptionally "reliable" distribution system, the secondary network system, was developed in commercial areas of the island of Manhattan. This consisted of a solidly connected grid of heavy copper cables at 115 V ac surrounding every block and fed by interleaved but not interconnected 12.5-kV cables originating at a number of power stations at the edges of Manhattan. There was no interconnection (built or in operation) between the power stations at 12.5 kV only on 115 V, and no fuses or cutouts within the 115-V network. This was indeed an extremely reliable energy supply at the distribution level for heavy density areas under conditions of only mild disturbances (115-V short circuits or losses of individual 12-kV lines or units). Modified versions are in use today worldwide.

Unfortunately, no analysis had been performed on what would happen under catastrophic disturbances. In about 1937 an ice jam came down the Hudson and forced the shutdown of one of the power stations. This resulted in cumulative overloading and shutdown of all the other stations, producing a complete blackout of Manhattan that lasted more than a week because the 115-V grid had to be sectionalized by saws before it could be reenergized. Interesting accounts were published about this event in Electrical Engineering (the publication of the American Institute of Electrical Engineers) in the years after 1937. These experiences made it clear that one must always look at the whole picture--all aspects of a large system operation, not just some limited facets of it. Unfortunately, the industry does not seem to have clearly arrived at this conclusion because the history of the decades since show a repeating scenario. Systems of great reliability were built up for a relatively narrow set of operating conditions. At the same time these systems were left open to catastrophic collapses under severe conditions. Typically, the same outstanding properties that make the system reliable for a limited set of conditions, which are considered in the planning, also make it vulnerable in more severe conditions. In fact, the industry may be in just such an exposed situation today in the midst of the feeling of reliability provided by the large control centers monitoring system security. To keep these remarks short, only two more historical examples will be given.

By the mid 1950s, load frequency control and economic dispatch had developed to the point where it became feasible to operate individual power companies quite independently within a large interconnected network. Because interconnection offered economies and reliability up to a point (typically the loss of a large unit), the size and loading levels of the interconnections grew rapidly.

Unfortunately, effective tools (that is large computers and effective load flow programs) for coordination and evaluation during abnormal conditions were not readily available until the mid 1960s. In their absence, no real coordination was possible during severe abnormal conditions. Thus, when severe abnormalities occurred in 1965, a cumulative collapse affecting 10 northeastern states and lasting about a day did occur--the widely noted Northeast Blackout.

Industry response was wide ranging and impressive, although not truly comprehensive. The NEPSIC, later NERC, organization was established, and, utilizing the fruits of the computer age (which got underway about that time), large-scale control centers were built.These centers were put to extensive use monitoring system security with several large commercial program packages for load flow and security computations. The latter means that system behavior is analyzed for specific disturbances--that is, contingencies--which are anticipated. Because of the overwhelming computational burden, only "first contingencies" can be checked, one disturbance at a time, and only in simplified and nondynamic approximation. Little attention is paid to sequences of disturbances or, in general, to flexible on-line responses when unexpected contingencies strike. In other words, little work was done on emergency control or restoration. (An historical parallel exists in the extensive and expensive fortifications of the Maginot Line, Corregidor, and Singapore which were all built for the contingency anticipated by the planners. None had mobile defense forces, i.e., flexible defense or emergency control, to deal with the contingencies that actually occurred [flanking attacks from the back side]). All three of these efforts at security proved useless in World War II. Hence, "Maginot Line philosophy" seems to aptly describe the heavy reliance on security monitoring in the power industry).

The basic scenario again repeated itself in the events of 1977 in New York. The system was secure in the first contingency sense, but it collapsed and Manhattan was again blacked out after three or four contingencies occurred in sequence. Furthermore, the disastrous consequences of this event were almost entirely preventable by flexible and appropriate emergency control and restoration measures. This fact was understood by the industry, but since the 1977 events in New York moved slowly and were still of limited complexity, competent manual emergency control by the human operator could have avoided most of the damage. Hence, the industry response again concentrated almost exclusively on upgrading operator training, including the building of power system simulators for operator training for emergency and restoration. Numerous programs, seminars, and workshops on operator training are continuing to the present.

Security and operator training are both exceptionally valuable attributes of operating today's large power system, but the unlearned half of the lesson is that major disturbances can be both too fast and too complex for even the best-trained and most competent human operator to handle. Automated emergency control and restoration measures are needed to aid or supplement the human operator under such conditions. Because of the almost complete absence of such comprehensive, flexible, automated emergency control and restoration measures, the industry remains exposed today to the possibility of another major collapse resulting from fast moving severe conditions beyond first-contingency security and operator capability. Coordinating the scope of on-line security monitoring and emergency control that must take over in actual disturbances is also awaiting systematic study.

About the only systematic, full-perspective research work on flexible automated emergency control and restoration to deal with major unanticipated contingencies has been done under sponsorship of the DOE program on electric energy systems. While this work was well planned and of broad scope covering the whole spectrum of conditions from stability problems and on line stabilization to slower moving viability crises and restoration, it is incomplete. Further research efforts are needed to lead to an eventual implementation phase. From the preceding analysis of the recent history of the industry, it seems to be clear that such research will only be done through a continuation of government support through DOE. Eventual implementation would be taken over by the industry, particularly EPRI, in the natural course of events.

An historical sketch (oversimplified in part to keep it reasonably brief) of the emergency control and restoration area was used in the preceding to illustrate the nature of the very real problems confronting electric energy systems. Government-supported research is needed in this area to supply long-range and wide-angle perspectives in identifying and developing research on such problem areas that pose a real and severe threat to the reliability of the power supply, yet fall outside the scope and range of activity of private industry sources.

A few details, including the sketch of a five-year schedule, follow for a few of these problem areas.

Emergency Control and Operation

The need exists for automated control and operating procedures (with human involvement in the slower regimes) that can flexibly counter unanticipated, usually multiple, contingencies not included in the ongoing security monitoring. Such unanticipated events (including those on other systems) are the potential sources of a future major system collapse or blackout.

Current industry work concentrates mostly on individual details of the problem. Comprehensive processes were proposed and studied in several projects under DOE sponsorship.

Sketch of a Five-Year Schedule

Years 1 and 2	Analysis work for comprehensive understanding of the needs and the merit of solutions already proposed either for specific component problems or comprehensively, including identification of the abnormal conditions and dangers they pose. New approaches not previously proposed should also be explored. Selection of one or more preferred approaches.
Year 3	Development of production-grade software and implementation plans for some selected systems.
Years 4 and 5	Numerous scenario studies for the target systems by simulation and gradual implementation on the actual system with carefully planned testing, initially in an advisory mode for the operator and gradually on line.

This sequence is intended to close a dangerous gap in state-of-the-art industry practice in an orderly sequence involving a five-year effort.

Role of Reactive Power in Emergencies

Increasing voltages and system loads have brought the reactive power problem to a situation in which voltage collapse becomes a possible hazard for systemwide service continuity. Major breakdowns resulting in the blackout of both France and Belgium in recent years were connected with such problems. Substantive research efforts sponsored by EPRI in this area provide effective algorithms for designing reactive power sources and their distribution into the system. A true understanding of these phenomena in system operation, especially under severe abnormal conditions, and effective on-line control means are still not available, however. Again, this work requires wide-and long-range perspectives not available in private sources of research support. It is also a component of the emergency control and operation problem, but special treatment--because of its special nature--is indicated, lest it become a neglected segment where potential major problems lurk. Also, it is less well developed and understood than other emergency aspects.

Sketch of a Five-Year Schedule

Years 1 and 2	Development of a thorough, clear theoretical understanding of the phenomena involved in the large-scale system context. Approaches to monitoring reactive power conditions and controlling them in emergency situations.

Years 2 and 3 Development of reactive power control and management processes and their evaluation by extensive simulation. Selection of preferred solutions.

Year 5 Development of production-grade software preparatory to implementation on selected systems.

Role of the High-Voltage Direct Current HV-DC Component (Two or Multiterminal) in Power System Emergencies

The situation is somewhat similar to that in reactive power (or to the extensive interconnections in the 1950s and early 1960s). The industry is embarking on a new course without a clear understanding of its implications, especially the dangerous unanticipated ones (such as that leading to the Northeast Blackout of 1965). Such dangers may be inherent in the HVDC component. For instance, if HVDC is not used for stabilization control, a system with a parallel HVDC component is generally less stable than an alternating current (ac) system designed for the same function. Conversely, HVDC can provide a very effective tool for stabilization, as shown in one DOE-sponsored project.

More details and a five-year sketch for HVDC/ac development will be presented in the next section, which deals with missed opportunities rather than unanticipated dangers.

Exploiting Opportunities for Upgrading System Performance by More Advanced and Sophisticated System Operation and Planning Methods

The state of the art in computer-aided system operation and control develops by small industry-supported short-range R&D steps, thus perpetuating the engineering solutions of an earlier technological age of electromagnetic relaying and instrumentation and analog computation. In this process the large-scale opportunities offered by the new general advances in computation and system technology are often by passed. The system then remains much less reliable or efficient than is possible today. High-priority government-supported research is needed in certain areas to help upgrade power system operation and security by wide-horizon conceptual research in the context of up-to-date computational and system or control technology tools.

The stunning Northeast Blackout of 1965 caused a strong interest in monitoring and control techniques and the large-scale data acquisition equipment they required. Very large-scale control centers consisting of successive generations of fast developing digital equipment were established. The newest generation of control centers are now in the planning stages at many U.S. utilities.

On the software side the story is more uneven. It can be separated into three disparate branches of development:

1. Bold new developments occurred where no prior technology existed. The computers proved to be very effective in monitoring and logging the system condition (SCDA). New elaborate techniques were developed, which were not possible before the digital computer, techniques such as load flow computations on large nonlinear networks for which many commercial programs are now available. On-line state estimation is applied on a number of utilities facilitating the detection of wrong measurements but typically too slow to track most emergencies. Security monitoring by checking large numbers of assumed contingencies became a widespread, large-scale operation with large demands on computer time. The optimal load flow after 25 years is still in the process of approaching on-line use on large-scale systems.

2. In such traditional areas as automatic generation control, protective devices, and various central and dispersed control functions, time-honored solutions of the past were simply programmed on the digital computers (central or dispersed) to replace their original electromechanical or analog implementations. The results of this approach may be no more than equivalent to the old solution and may pass up the great potentialities of the new powerful tool, the digital computer, and new systems and control technology.

3. The third area is represented by important operation and control problems that do not have traditional solutions and also have not been resolved using digital computer techniques. No state of the art has yet emerged for such important areas as the recognition of emergencies and the development of measures for emergency containment and remedy and for restoration.

Correspondingly, there are numerous situations in the power system state of the art today in which--while acceptable operation is maintained--it requires much larger effort and is much less effective than possible because of the limited perspective of the industry's development.

Consequently, truly major opportunities for improvement abound. A few will be mentioned.

Automatic Generation Control

Automatic generation control is still utilizing techniques developed in the analog control era, although these analog controller functions are now carried out on powerful digital computers that are capable of handling much more sophisticated approaches. Increasing sophistication is needed mainly for two reasons: (1) because increasingly heavy system loads make it necessary to enforce, on line, loading constraints on equipment, and (2) because the recently developing free market and exchange type (cross-system) trading of power between companies imposes a much more complex control problem on the operation of the large interconnected system. Excellent initial work, including a practical demonstration of some early results on the Wisconsin system, was supported by the DOE-EES program. Much more is needed, however.

Sketch of a Five Year Schedule

Years 1 and 2	Analyze the problem area in terms of what is needed and evaluate capabilities of the state of the art, including the improvements demonstrated in the Wisconsin project and proposed but as yet unimplemented solutions. Develop new comprehensive solutions that include control of loading and voltage limits on the system in terms of active and reactive power, energy trading, and primary and secondary inadvertent interchanges.
Year 3	Select one or more preferred solutions on the basis of analysis and experimentation by simulation.
Years 4 and 5	Develop production-grade software; make preparations for implementation; and initiate implementation, tests, and demonstration at selected locations.

Restoration

Utilization of current computer based technology for large-scale restoration is an extremely complex problem. Three directions of study exist:

1. Individual utilities are studying restoration practices of specific pieces of equipment, such as steam units.
2. Individual utilities are making plans for restoring their system, under computerized failure conditions. There is a lack of flexibility and comprehensiveness in this approach.
3. One DOE-sponsored study and one or two other less detailed ones follow a comprehensive and general approach and show very promising progress.

A five-year schedule, somewhat like that for emergency control, is indicated.

The Compound HVDC/AC Systems

With increasing system load, HVDC plays an increasing role in the power system. A clear understanding of the operation of a system that contains both ac and dc elements in comparable amounts is essential for this development and the forceful beginnings under support by the DOE-EES Program should be continued. Great possibilities exist for utilizing the fast response and easy control of such systems in emergency and normal conditions:

1. Emergency control, specifically in stabilization, has already been discussed.

2. Possibilities also exist in viability crises in which load flows must be controlled on line to eliminate overloads in certain areas.
3. In normal state AGC, the HVDC system can be very efficient in controlling such problems as "loop flows" or "wheeling."

A more general aspect of the HVDC problem includes the proper use of such other thyristor devices as static Var control equipment.
On the debit side the harmonic generation and reactive power demands of the converters also need to be studied.

The Reactive Power Voltage Problem

This was already treated on the emergency control side, but it has equally important implications for several state control. Recent work sponsored by EPRI provides a good foundation for computations, but without a thorough theoretical understanding of the true possibilities, it will not be exploited.

Selective Protection

Selective protection of the power system, although now increasingly digital, is still based on the principles developed for the constraints of electromechanical relay-type instrumentation. This state of affairs is clearly obsolete, inadequate, and conducive of widespread disturbances. A complete rethinking in terms of today's digital technology is overdue.

Creating a Supply of Sophisticated Researchers for the Age of the Control Center

With the increasingly dominant role of the large control center and its extensive digital computer equipment for power system operation and control, a need arose for personnel, ranging from operating personnel to sophisticated researchers employed by the power utilities, supply industry, and universities. These researchers must be fully versed in two distinct technologies'.

1. The operating and control needs and practices of the power system, and
2. the systems-mathematical programming-computing technologies on which the new operating and control practices are based.

These are two rather different technological worlds and good research on modern power system practices cannot be done without being at home in both. Cooperation of experts from the two technologies did not prove satisfactory, nor should it be expected to be satisfactory. In fact, much of the remaining interface noticeable in much of state-of-the art practice resulted from this approach and is in turn responsible for much inefficiency in the state of the art.

The only source of such expertise in young researchers for the last 15 years was participation through thesis activities in advanced research sponsored at some universities by the EES program in DOE (and previously in ERDA and NSF-RANN). Most of the young graduates who emerge from this research remain in this challenging field. Many have reached influential leadership status through their highly useful technical contributions.

The current drastically reduced status of the research supported by the EES program results in an effective shutoff of the flow of this needed research talent into the power industry. For instance, at one university 17 D.Sc. degrees were awarded in the last 10 years with theses in this area. All were eagerly employed, mostly in industry, with top starting salaries. Several are pursuing visibly successful careers. In the current situation it seems that two more students will graduate in about two or three years with no further succession likely given the current funding levels.

CONCLUSIONS

The preceding represents only a few examples in which wide scope and a long-range approach to research on the power system is required. There are numerous other such problem areas; many more are certain to arise.

In summary, while its accomplishments are impressive, the computer age has arrived in the power industry but incompletely, and in sometimes short-range and limited-purpose development, often in the form of simply programming existing control and operating practice on the digital computer without exploiting its true capabilities. This situation leaves two disturbing concerns:

1. Unattended large gaps were left by the growth of control center software (e.g., in emergency control, reactive power-voltage stability, restoration, selective protection), resulting in a situation analogous to that created by the limitations of the system practices prior to the Northeast Blackout of 1965.
2. Certainly, more complete, more efficient, more effective and less computation-intensive alternatives exist to the state of the art.

Systematic research with a long-range viewpoint to upgrade current practices and to identify and close hazardous gaps in the state of the art of operating and controlling the large power system by digital computer techniques is urgently needed. Considering the current state of the industry, it can be supplied only by governmental support .

The Electric Energy System programs in DOE seem to have filled this role distinctively, and effectively. They have also provided imagination and good realistic planning, particularly in reliability as the term is used in this workshop.

COMMENTS FOR PANEL REVIEW

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MATERIALS

Basic research on materials is fundamental to all processes involving electric systems. The relevance of the relatively young Oak Ridge National Laboratory (ORNL) materials program was not addressed. Considering the existing programs in the materials centers in universities (sponsored by NSF), the materials work in industry, and materials work in other national labs (LLB, for instance), the specific program at ORNL needs to be placed in context. For example, if ORNL materials was supported as a basic program supporting EPRI's applied program, it could be a very attractive and desirable role for DOE with its long-term national mission.

In conclusion, just doing materials work is not enough. Some basis for choosing among an infinity of basic materials work is needed. I believe DOE has a role to play in long-term materials research in electric systems.

SUPERCONDUCTORS

The balance between long-term research and applications was not addressed. Very good programs on generators, transmission lines, and energy storage have been conducted in universities, industry and materials labs. The balance today between application and materials research on improved superconductors needs attention.

I believe what is needed is a careful rendering of the evaluation of the future program in superconductor research, which requires more information than was available at this meeting.

HAWAIIAN CABLE PROJECT

This is a pork barrel project. NRC should not justify its existence on the basis of research to transfer technology to U.S. industry. Call the project what it is. Don't prostitute the research community on projects such as this.

HVDC

Research needs were identified for:

- o DC circuit breakers,
- o multiterminal systems,
- o forced commutating circuits, and
- o national grid/bulk energy exchange.

The specific role of DOE was not addressed and should be. I recommend identification of a set of specific R&D activities. Because of work in other places, it could be zero at DOE.

LOAD LEVELING

Near-term load leveling activities were described. These are clearly of benefit to the utility industry, and EPRI is a major contributor; however, the need for long-term research on load leveling was not established.

There is no significant role for DOE in load leveling. However, long-term basic research in electrochemistry and batteries may be a logical role for DOE, and a modest, sustainable program in national labs and universities is probably what is needed. DOE has a very poor record in this type of basic long-term research.

ELECTRIC COMPONENTS

No role for DOE identified.

EMP

Protection of the U.S. electric grid is a national problem and must be addressed at the top federal executive level. DOE is not the place for dealing with EMP. EPRI is the logical agency to interact with government for the utility industry. The research should be federally funded--its national security, aspect is logically some part of the federal budget, possibly civil defense, or even DOD.

RELIABILITY - EMERGENCY OPERATIONS, EFFICIENCY, ECONOMIC TRADEOFFS

There is no logical role for DOE with its long-term focus. The industry and EPRI are the correct places for such research.

RELIABILITY - UTILITY NEEDS AND EXPERIENCE

There are research opportunities to improve economic and reliable operation of transmission lines. Such studies must be closely related to real systems. The industry and EPRI are best suited to carry out the needed research.

DOE is not the best organization to manage research on the economic and reliable operations of transmission lines. With limited resources, this is not a priority for federal funding. (An exception would be a major study of a national grid, which probably would only be undertaken at the federal level. A national grid study should be undertaken by the industry, but because of social, political, and emotional factors the industry or EPRI could refuse to make the study.)

RELIABILITY - FAILURE MECHANISMS

This is a research opportunity. But detailed components and system data are required. It is not a priority to pick for DOE long-term funding. Industry/DOE technology interchanges do not exist and probably cannot be established. There is a fundamental role for EPRI and the industry.

ELECTROMAGNETIC EFFECTS

The biological effects of electric and magnetic fields are important and require much additional research. This is a social problem in which the federal government has a major role. DOE is the logical agency to fund this research but should have close cooperation with NIH and EPA.

RECOMMENDATIONS

Continue the DOE program but make sure the full resources of the biological/medical research community are utilized. My experience is that NIH monitors its environmental/health research better than DOE.

A BRIEF HISTORY OF THE ELECTRIC ENERGY SYSTEMS R&D PROGRAM, 1970-1981

Francis Fox Parry

INTRODUCTION

This account has been compressed in the interest of brevity and clarity; a full history would require volumes. A few memos or pages thereof have been included as appendices, which speak to points of specific interest to the committee, such as the organizational location of the Division of Electric Energy Systems (EES) and staffing problems.

The EES R&D program had its genesis in 1970 in Department of the Interior (DOI) sponsorship of the Electric Research Council (ERC) underground transmission R&D program. This program had been selected for federal support because it was the largest and most comprehensive effort of the ERC (in its final ERC year, 1973, consuming 43 percent of the budget) and because it addressed a clearly definable need to reduce the cost differential of underground to overhead transmission then estimated at 10-20 to 1.

This heavy financial penalty was being imposed upon consumers in urban areas as well as in the vicinity of historical sites or other environmentally sacrosanct areas. Consideration for the environment was another key motivation for this pilot program in government-industry cooperation, but the principal thrust was the desire to stimulate industry effort in the broad spectrum of electric power systems research.

OFFICE OF THE ASSISTANT SECRETARY, WATER & POWER, DOI (1970-1973)

There was an obvious advantage in having the incubation period of this R&D program within the front office. With direct, daily access to the assistant secretary and his deputy, it was an easy matter to invoke high-level pressure to overcome roadblocks on those few occasions when real resistance was encountered. A case in point was the general counsel's reluctance to enter into three-party contracts (i.e., DOI, Edison Electric Institute (EEI), and the R&D contractor), a necessary condition to the establishment of a joint government-industry program since federal regulations required that government funds be accounted for by government contracts. During the first three years of this joint effort, 26 three-party contracts were written in which federal funds varied from 50 to 10 percent, depending upon the degree of interest in the project; total federal funding, however, could not exceed 20 percent of the joint program, a restriction imposed by the Congress that was carefully adhered to.

During this period the program was technically managed by the ERC Underground Transmission R&D Program Steering Committee, with DOI administering the contracts. The committee numbered in its ranks the top industry talent in the field and was responsible for, among other things, the activation of the Waltz Mill, Pennsylvania, Underground Transmission Test Facility. Within DOI, technical advice was available primarily from the Bonneville Power Administration (BPA). Inasmuch as BPA had no underground transmission, however, the DOI program manager leaned heavily on key committee members with whom he had established excellent rapport. While the committee and its several task forces soon numbered over 50 engineers in the attempt to professionally manage the burgeoning program ($10 million in 1973--$8 million, EEI; $2 million, DOI), it soon became apparent that planning for and management of so large and diverse an R&D program was beyond the means of a part-time committee, no matter how competent.

INDUSTRY-GOVERNMENT MAJOR PLANNING EFFORTS

From 1970 to 1973, industry and government produced three landmark studies addressing the long-term R&D needs of the electric utility industry. These were: (1) <u>Electric Utilities Industry R&D Goals Through the Year 2000</u>, Report of the ERC R&D Goals Task Force, June 1971; (2) <u>The Federal Council on Science and Technology R&D Goals Study</u>, July 1972; and (3) <u>The Nation's Energy Future</u>, A Report to the President of the United States by the Chairman, Atomic Energy Commission (AEC), December 1973. The DOI program manager was fortunate in participating in all three: in (1) as the chairman, of the Subcommittee on Organization and Administration of the proposed Electric Power Research Institute; in (2) as the chairman of the Technical Group on Electrical Transmission and Systems; and in (3) as the chairman of the Panel on Energy Transportation, Distribution, and Storage. These studies, as well as others, such as the Federal Power Survey, outlined the scope and projected cost of the R&D effort confronting government and industry and suggested areas in which this effort should be concentrated. In addition to the education afforded by such association with top industry planners and engineers, participation in all ERC meetings and, later, EPRI board meetings (first as the responsible DOI staff member and later as an acting board member from 1970-1974) gave the DOI program manager added insight. He became familiar with the problems a regulated industry of some 3,000 utilities of varying size, financial resources, and political complexion had in marshalling a meaningful R&D effort.

Springing directly from these activities were the activation of the Electric Power Research Institute (EPRI) in 1973 and the Energy

Research and Development Administration (ERDA) in 1975. Whereas the federal government wished to encourage industry to organize a major R&D effort of its own and come to grips with the technological challenges which a changing international situation and concern for a deteriorating environment were bringing to the fore, it realized that a major federal effort would also be required.

OFFICE OF R&D, DOI (1973-1975)

Within the Department of the Interior, the Office of R&D was established to accelerate research in fossil fuel. Dr. Bill Gouse, the director, concentrated on preparing the Office of Coal Research for a major effort. He did, however, bring the small underground transmission program under his wing; elevated the manager to the position of Assistant Director, Transmission, Transport, and Storage; and gave full support to expansion of the program to encompass all power delivery systems and energy storage. Dr. Gouse had become familiar with the research needed in electric systems and storage through his participation in the FCST and AEC studies of 1972 and 1973; his wholehearted, knowledgeable support, coupled with a management style that called for interference only when a program was being mismanaged, provided an ideal environment for program expansion.

With a budget of about $10 million and previous restrictions of the joint program lifted, the assistant director exercised his contacts developed over the previous four years to ferret out industry talent interested in developing an imaginative, aggressive R&D program. Four top engineers were recruited: Les Fink from Philadelphia Electric with experience in the control problems of the Pennsylvania-New Jersey-Maryland interconnection to initiate systems engineering R&D; Dr. Howard Feibus from Consolidated Edison, possessor of the world's largest underground transmission system, to take over underground transmission R&D; Bob Flugum, director of Ohio Brass' overhead transmission test facility to initiate overhead transmission R&D; and Ken Klein of Cleveland Electric Illuminating, whence had come the earliest plans for distribution R&D, to initiate R&D in that area. These senior engineers then brought aboard such talented assistants as Bill Feero (transient analysis), Tom Garrity (gas insulated substation equipment), Dr. Kjell Carlsen (systems engineering), and Charlie Smith (energy storage). Within less than two years, twenty eight professionals were at work. Of these, ten had electric utility experience, eight came from electric equipment manufacturers, six from universities, and only four from the federal government. It was this carefully recruited, talented group of engineers, well versed in electric utility industry planning and operational problems, that was responsible for the quality of the R&D program and the interest it soon evoked throughout this country and abroad. There is ample evidence to support the contention that this federal R&D program was unique, with its highly competent, industry-recognized staff more conversant with the industry problems that the program addressed than comparable federal R&D efforts. It is fortunate that this was so, for the program would soon face a series of challenges to its existence and its survival was in considerable measure due to strong, consistent support from industry.

A brief analysis of the foundations upon which this support rested is germane. An obvious basis, of course, was the fact that almost 90 percent of the staff came from industry and had wide, influential industry contacts that were nurtured by individual participation, wherever possible, in such technical committees as IEEE and CIGRE. Energetic participation in industry-sponsored meetings, such as the Transmission and Distribution Conference and the Winter and Summer Power meetings, also kept as many communications channels as possible open. Perhaps most meaningful of all, however, was the regular participation in the EPRI industrial advisory structure. As an architect of EPRI, the program manager was intimately familiar with the industrial advisory committees and task forces and their value to researchers in keeping projects directed at real problems. Participation in these groups, first as members while in DOI and later as invited guests during the ERDA and Department of Energy (DOE) days, was an act of faith for this program, only being reduced in scope when personnel losses dictated. Industry, accordingly, was well aware of its stake in the program and could be counted on for support when needed.

ERDA CONSERVATION (1975-1977)

With the formation of ERDA in early 1975, the DOI Office of R&D as well as other infant energy R&D programs from the National Science Foundation and elsewhere in the federal establishment joined AEC R&D programs, now divorced from the regulatory arm. In an attempt to suggest a substantive effort in conservation R&D, ERDA management collected under the conservation umbrella small programs with no obvious home, such as DOI Transmission, Distribution, and Storage. Consolidated with AEC superconducting transmission R&D projects, this program now sought a more appropriate name. In initial discussions with the Acting Assistant Administrator for Conservation, Dr. Jim Kane, agreement was reached that generation not associated with a specific fuel (fossil, nuclear, solar), such as fuel cells and all types of energy storage, would be included in the program. This led to the relatively inclusive program name of Electric Energy Systems (EES). Later, Dr. Kane decided to incorporate the laboratory-level research in generation and storage in another division, with EES retaining responsibility for R&D in these areas when they were ready for system demonstration. It was from these early "turf" decisions that EES became sponsor of the 4.8-MW fuel cell demonstration on the Consolidated Edison system and Battery Energy Storage Test (BEST) facility on the Public Service Electric and Gas system. It was also from these early "temporary" decisions that budget support for these important projects was allowed to remain in the generation and storage budgets ("so they'd appear to be legitimate divisions") rather than being incorporated in the EES budget, as repeatedly requested and frequently promised. Such compromises with sound management principles rarely pan out, as demonstrated five years later in the 4.8-MW fuel cell fiasco.

It soon became apparent that the incorporation of EES and, to a lesser extent, the research programs in non-fuel-related generation and energy storage in Conservation had not been wise. Both the ERDA Conservation administrator and the Congress had trouble justifying these as conservation programs. For this reason, funding support, particularly for EES, was restricted to modest increases while other conservation R&D programs then in vogue received increases many times that which they could reasonably absorb or properly manage. ERDA and the Congress both recognized the value of the EES program as evidenced by Senator Jackson's letter and the response thereto (Appendix 1*, Attachment A), but the fact that it was buried under a Conservation hierarchy whose reputation would rise or fall on its accomplishments in the conservation arena presented a continuing problem for EES. Despite this handicap, it was during the ERDA period that the first important ties were forged with the congressional staff, and an understanding of the need for and basic motivations of the EES program took root. Nurtured by the quality and demonstrated successes of EES R&D projects, this understanding has proven to be the bedrock of support critical to EES survival. For this program, with no constituency** free to rally to its support, such as the fossil, solar, nuclear, or conservation advocates, had to survive on its own merits. One thing that EES thought it had going for it was its close relationship and established modus vivendi with EPRI--in the ERDA days, it was cited as a model of government-industry cooperation. But with the advent of DOE and its regulator-dominated, anti-utility bias, this seeming virtue overnight became a liability.

ENERGY TECHNOLOGY (SOLAR), DOE (1977-1979)

When ERDA was absorbed into DOE, the opportunity to realign the orphan conservation R&D programs "more appropriately" was taken advantage of. Generation research was allotted to Fossil, energy storage to Solar, and EES to Nuclear. The reasoning behind these decisions was obscure, if indeed there was any beyond an equal division of the spoils. Energy Storage was the most logical assignment as the solar technologies had obvious need for a viable storage R&D program--but then so did the electric vehicle, which remained in Conservation. Fuel ccll R&D, which

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*A list of appendices is provided, but the appendices are not published within these proceedings.

**A regulated industry, electric utilities do not lobby the Congress.

represented most of the Generation budget, had been voluntarily awarded to Conservation by Fossil at the outset of ERDA, so its return to Fossil seemed hardly a matter of urgency. Incorporation of EES in Nuclear was even more unfathomable and would have consigned to quick demise its incipient, though significant, program to fit the new distributed technologies (wind, photovoltaics, etc.) into the electric power system successfully. Confronted with these uninspiring options, EES determined that of the three available choices, Solar appeared to be the most promising. The Solar program was rapidly expanding and had a clear (though unacknowledged) need for power system engineering scrutiny and guidance. Further, our "sister program" Energy Storage was in Solar and there was some advantage perhaps to be gained by mutual support. So after three weeks in ET-Nuclear, EES negotiated a transfer to ET-Solar.

The ensuing period, from 1977-1979, though embarked upon with enthusiasm and the conviction that EES could make a positive contribution to national policy objectives, soon became a passage of continuing peril. ET-Solar was finally persuaded to give EES responsibility for electric power system interface R&D and allow it to deal directly with the solar technologies--a relationship EES had sought to bring about for over two years (Appendix 2). Reluctance on the part of Solar to allow EES engineers to scrutinize their programs was no doubt legitimate from their point of view, as several projects were soon found to have basic system integration problems that prior EES analysis would have uncovered. Simultaneously, in conjunction with ET, decision makers were wrestling with various options for dismantling EES. The parts of the EES program that came under assault were bulk power transmission R&D and long-term, theoretical system engineering studies. Apparently, ET-Solar's objective was to force the organizations most interested in these programs to support them through pass-through funding, a ponderous, unreliable procedure at best and one calculated to bring about the early collapse of EES (Appendix 1). Then the remaining fragment of EES concerned with solar technology power system integration problems could be reduced to branch level and tucked conveniently into the Solar central staff organization. This threat to EES existence was partially stymied within DOE by letters of support from ET-Nuclear, ET-Fossil, Economic Regulatory Administration, and Resource Applications (Appendix 1, attachments). This evidence of in-house DOE support for EES did not, however, deter ET-Solar and its ET headquarters allies; it only called for a change in strategy. An "assessment" of those elements of the EES program under attack to determine the strength of industry support was now required before ET would support an EES budget. Anything less than a ringing endorsement would have been enough for the ET program wreckers. To help ensure a "suitable" outcome, a steering committee consisting of the chief ET program planner, the ET-Solar deputy (the two most intent on EES dismantlement), and the EES division director was formed. Undaunted, EES took the bull by the horns, scheduled meetings both in Washington and the field, and rallied industry to the cause. The "Steering Committee" was quickly outmaneuvered. Utility, university, and electric equipment manufacturer spokesmen of unimpeachable stature rose to the EES defense, as did EPRI and BPA. While this highly favorable assessment validating strong industry support was enough to keep EES afloat into 1979, it was the replacement of Bob Thorne by Dr. John Deutch as ET assistant secretary that finally brought some succor to EES. Nonetheless, ET-Solar was by no means finished in its quest to bring EES to bay. While frontal assault was now impolitic, it resorted to more subtle attrition tactics. Transfer of EES personnel slots to the "centralized Staff" (Appendix 3), requisition of EES funds for a solar village project in Saudi Arabia (with no conceivable electric system integration connotation), and the proposed activation of a "Projects Office" to manage large, construction-type projects (BEST was one of the candidate projects to be taken from EES) are examples of such tactics. This continuous harassment forced EES to divert resources to its own defense that were needed to plan, manage, and coordinate (within DOE and with EPRI) its R&D program, which amounted to an annual budget of about $60 million (of which one-third were pass-through funds from Fossil, Storage, and Solar).

The Solar era was a continuous battle to keep the EES program viable. Although it resulted in the inauguration of some valuable, new, distributed generation power system integration studies, it also convinced some of EES' most talented engineers that federal R&D was needlessly fraught with fratricidal warfare, and they began to depart for the more predictable perils of the private sector. Upon Dr. Deutch's promotion to undersecretary in 1979, further private appeals were made to him by EES to forestall the continuing ET-Solar depredations. He responded by personally taking over justification of the program before the Congress and directing the addition of $10 million to the program budget. He also promised to find EES a more compatible home, which he did when DOE was reorganized in late 1979.

From 1975 to 1979, the five most productive years of the program, EES had survived, though somewhat scarred, two critical organizational misplacements--Conservation and Solar--to both of which only minor segments of its R&D applied. Including the prior year in DOI, EES had served in all four of the major R&D organizations (Fossil, Conservation, Nuclear (albeit briefly, and Solar). Clearly, it could not prosper under managements whose focus was on a single fuel-oriented or energy-saving technology. So EES was assigned to Resource Applications (RA), the residence of the Power Marketing Agencies (BPA, Western Area Power Administration, etc.), where it was hoped that it could make a secure home.

RESOURCE APPLICATIONS DOE (1979-1981)

The mission of Resource Applications was to speed DOE-sponsored technology, other than that of the Conservation and Solar areas, toward commercialization. The EES distributed generation and energy storage applications programs, load management, and some projects in power delivery suited this mission. But, once again, important elements of the program, such as the long-range systems engineering subprogram, were more related to the fundamental studies of the Office of Energy Research as was the low-loss amorphous metal research for motors and generators. A brief description of the EES program thrusts at that time is in Appendix 4.

The RA high command, no doubt aware of the undersecretary's sponsorship, was hospitable to EES. The new assistant secretary, Dr. Ruth Davis, had excellent rapport with the electric utility industry as a result of her service on the EPRI advisory council and made known her strong support of the EES program. The two deputy assistant secretaries, first Dr. Stan Weiss and later Rudy Black, were consistently supportive (Appendix 5). In this more compatible environment, EES decided to attempt to resolve two long-standing issues that had rendered management of two important subprograms--the 4.8-MW fuel cell and energy storage applications--most difficult.

THE 4.8-MW FUEL CELL CONTROVERSY

EES had initiated the 4.8-MW fuel cell demonstration project in 1975 and had managed it throughout its existence. The budget, however, had always been carried elsewhere, first in another division of Conservation and then, after 1977, in Fossil. This had represented a minor inconvenience while we were all together in Conservation, and the assistant administrator had repeatedly promised to transfer the 4.8-MW portion of the fuel cell budget to EES at the first appropriate time. Unfortunately, this promise was lost in the shuffle when ERDA disappeared into DOE and the assistant administrator returned to the private sector. Since that time Fossil had emphasized the longer range fuel cell technologies that it managed and had short-changed the 4.8-MW, despite industry advice to the contrary, making little effort to defend the demonstration project either within DOE or on the Hill. In the ensuing effort to wrest budgetary authority for the 4.8-MW program from Fossil, some of the RA management was hoodwinked. The resulting decision to transfer management from EES at the crucial stage of that key project was certifiably one of the most ill-advised, short-sighted blunders orchestrated by the young department already familiar with picking wrong horses. (See Appendix 6-- just one of scores of memos on the subject.)

In contrast to the 4.8-MW fiasco, the budget responsibility for storage applications, including the BEST program, was quickly and amicably settled by the respective deputies, Dr. Stan Weiss for RA and Dr. Maxine Savitz for C&S. EES was awarded budget authority to go with the management responsibility it had always had.

CONCLUDING COMMENTS

With the disappearance of Resource Applications in 1981 and the return of EES to Conservation for apparent want of a better place to house this persistent orphan, the dreary cycle of organizational misplacement began to repeat itself. EES does not belong in Conservation any more than it belongs in Nuclear or Fossil or Solar. Nor, for that matter, does Energy Storage, another orphan almost as ill used as EES. These two small R&D programs have had consistent support from the Congress for over a decade and address long term problems of national interest. Coupled together in the Congressional budget since 1975, they deserve a better fate than being uprooted and having to rejustify their existence every two years. Both have roles that transcend one technology; it defies logic that they are not organizationally placed where they can carry out their missions most effectively. Even their programs are compatible inasmuch as the main energy storage thrust is to develop batteries for load leveling and electric vehicles, both dealing with electric system problems or accommodations of obvious import to EES.

As it has been since 1975, my recommendation is that a combined Office of Electric Energy Systems and Storage report directly to the undersecretary. It is unlikely that such an organizational entity would prove inconvenient and it would be ideally positioned to do its job. If this option is nonetheless unacceptable, such an office could alternatively be incorporated in some relationship with the Office of Energy Research, whose long-range efforts similarly have application across the board.

Perhaps as good a measure as any of EES program value is contained in the EPRI 1984 Annual Report. Of the 20 research highlights cited by EPRI from more than 1,500 projects, three were initiated by EES: (1) Reducing Transformer Losses (page 13), initiated by EES; (2) Advanced Batteries for Energy Storage (page 15), initiated by EES; and (3) Modular Power Plants Downtown (page 17), initiated by EES in conjunction with EPRI.

APPENDICES

1. Organizational location of EES, plus letters of support from Senator Jackson (Reply by Dr. Seamans), ET-Nuclear, ET-Fossil, ERA, (one from RA (BPA) misplaced)

2. System Integration of DG&S.

3. Personnel Resources + Plea for EES unique role in DOE.

4. EES Program thrusts (1979).

5. Personnel + outline of EES advisory role responsibilities.

6. 4.8mw Fuel Cell Comments.

Department of Energy
Washington, D.C. 20545

ACTION MEMORANDUM

TO: Secretary

THRU: Under Secretary

FROM: Assistant Secretary for Energy Technology

SUBJECT: ORGANIZATIONAL LOCATION OF THE ELECTRIC ENERGY SYSTEMS DIVISION

Issue

What is the best organizational location for the Electric Energy Systems Division (EES); and what is the best way to budget for the program?

Background

The organizational location of the Division of Electric Energy Systems is not a new issue. It has been raised on several occasions during the past two years. In ERDA it was the subject of a serious Congressional inquiry (see Senator Jackson's letter to Dr. Seamans and the subsequent reply, Attachment A); and in organizing the Department of Energy, EES was briefly in the Office of Nuclear Energy Programs (ETN) before being incorporated under the Office of Solar, Geothermal, Electric and Storage Systems (ETS). The final disposition of this matter was based primarily on the fact that the success of DOE's solar strategy will in large part depend upon the resolution of electric utility interface problems. The effective integration of distributed solar and storage into the electric network will determine how rapidly those technologies penetrate the energy supply system.

On the other hand, EES has executive responsibilities outside ETS to other programs within the Office of the Assistant Secretary for Energy Technology (ET), notably Fossil and Nuclear, and to other organizational entities within DOE, most particularly, the Economic Regulatory Administration (ERA) and the Office of Resource Applications (RA). These organizations fully endorse the importance of a strong EES program to achieve their goals. (Attachments B, C, and D)

The discharge of these responsibilities obviously requires funding work of specific interest to each group, as well as supporting generic activities that are of interest to all. The basic ET approach to funding these activities is for others to sub-contract with EES for selected R&D programs. But two problems have arisen in doing business this way.

First, the cross-cutting nature of much of the EES work means that no one organizational entity wants to assume the full burden for supporting activities that benefit so many others. For example, a technology like direct current transmission could be important to the siting of a nuclear or fossil power plant, or to any of several central solar technologies, or to the exercise of the emergency power transfer responsibilities of ERA, or expansion of transmission capacity of one or more of the power marketing agencies of RA. Secondly, it is not now within the mandates of ERA or RA to fund R&D.

The question then is how do we provide and defend in a rational way an adequate budget for this important program?

Alternatives

Option A: Transfer EES from the Office of Energy Technology (ET) to ERA or RA.

pro:
1. ET budget process is flexible enough to fund ERA or RA for R&D important to ET's mission.
2. If transferred to ERA, emphasis would be to solve Corridor Crisis; if transferred to RA, the pressure would be toward high capacity bulk power lines; both important issues.

con:
1. Would remove EES from intimate relationship with solar and storage R&D programs, and would hinder successful integration of these technologies into the electric energy system.
2. Would remove EES from close association with fossil and nuclear R&D programs.
3. Would place EES R&D programs in an essentially non-R&D environment.

Option B: Retain EES in ET, and alter ERA and RA budget procedures to enable them to sub-contract R&D funds to ET.

pro:
1. Would maintain high technology R&D in ET, consistent with its mission.
2. Location within ETS maximizes probability of successful integration of solar technologies into electric networks.
3. Continues to supply an independent technical resource for advice to both ERA and RA to support them in carrying out their missions.
4. Would allow ERA and RA to sub-contract R&D needs to EES.

con: 1. Altering the DOE budget process for ERA and/or RA might delay submission of the FY 80 budget. Three assistant secretaries would have to approve a relatively small budget.

2. Controlling a multi-faceted R&D program via annually negotiated pass-through funds, might inhibit total efforts because of split responsibility.

3. ERA and RA would relinquish some control of R&D supportive to their missions.

<u>Option C</u>: Retain EES in ET and budget their R&D within ET, after appropriate consultation with ERA and RA.

pro: 1. Total control and responsibility are maintained within EES for outcome of R&D.

2. Would maintain high technology R&D in ET, consistent with its mission.

3. Location within ETS maximizes probability of successful integration of solar technologies into electric networks.

4. Continues to supply an independent technical resource for advice to both ERA and RA to support them in carrying out their missions.

5. Allows maximum flexibility to meet national changes in energy policy in shortest span of time.

con: 1. Direct control of R&D supportive of the ERA and RA missions would not rest with them.

<u>Discussion</u>

The two principle problems being addressed by the EES program are:

1. Solving the Corridor Crisis, where electric power is prevented from reaching the load due to lack of sufficient rights-of-way over which to transport that power. The problem exists already and is mushrooming.

2. Integrating dispersed generation and storage technologies into the existing and future dynamic electric energy network. Electric system interface problems are on the critical path for many such solar and storage technologies.

Option A would remove EES from intimate association with solar technologies. It might more closely align the R&D efforts toward either the federal marketing agencies or the regulatory needs. It is difficult to judge whether a specific technology such as advanced underground superconducting cables will first become important to a power marketing agency (RA), the regulatory area (ERA), or energy parks (ETF or ETN).

In view of this cross-sectoral nature of the EES program and its critical role in the successful integration of all new source technologies, particularly dispersed solar and storage, the justification for its retention within ET appears to be overriding. Further, a new move to ERA or RA would place the jurisdiction of EES in an entirely new Congressional subcommittee structure where the broad based nature of the program would be less appreciated and understood.

Both Options B and C are acceptable, in that they are capable of meeting the EES program objectives. Each, however, has its strengths and weaknesses. Option B enforces a closer relationship with ERA and RA since they would be funding selected EES programs. This closeness would be to everyone's advantage. The price paid for this is far more complicated program planning and an extended budgeting time frame since three different Assistant Secretaries would have to approve before EES could have an agreed-upon budget level.

Option C would focus all planning and budgeting within one division (EES) making it totally responsible for that R&D program. And, as national priorities shift, it could respond more quickly; but this is counterbalanced by the natural institutional tendency for the program to become insular and thereby perhaps less responsive.

Recommendation

For FY 80, because of the advanced state of the budget cycle, I recommend that the controller provide EES with approximately $10-15 million in pass back funds, the exact amounts to be determined through consultation with ERA, RA and within my own organization. For FY 81, I recommend that Option B be exercised.

Approve: ________________

Disapprove: ________________

Date: ________________

Next Steps

1. Results of these discussions with controller, ERA and RA on FY 80 adjustments will be reported to you.

2. Begin negotiation with ERA and RA on FY 81 programs.

Concurrences

ERA	Date ____	Concur ________ Nonconcur ______	See Tab ________
RA	Date ____	Concur ________ Nonconcur ______	See Tab ________
CR	Date ____	Concur ________ Nonconcur ______	See Tab ________

Attachments: Tab A - Senator Jackson Letter and Dr. Seamans Reply
Tab B - Letter from ETN re: EES Program
Tab C - Letter from ETF re: EES Program
Tab D - Letter from ERA re: EES Program

Prepared by: ETS: BMiller/clr: 376-4102: 9/22/78

ATTACHMENT A

[illegible]

United States Senate

COMMITTEE ON
INTERIOR AND INSULAR AFFAIRS
WASHINGTON, D.C. 20510

March 17, 1976

Dr. Robert C. Seamans
Administrator
Energy Research and Development
Administration
20 Massachusetts Avenue
Washington, D.C. 20510

Dear Dr. Seamans:

In the course of our review of your proposed 1977 budget, a problem area has become apparent that we believe requires some attention. In the $120 million Conservation Office budget, $46.8 million is budgeted for Electric Energy Systems and Energy Storage Systems. The programs in this category appear to be both highly important and excellent in content, however, they are not generally considered to be conservation programs in the strictest sense.

The presence of this large segment of Systems work, roughly 39%, in the Conservation budget creates an impression of more effort on conservation than that actually underway. Furthermore, these useful Systems programs are likely to suffer over the years when competing internally for funds with the more legitimate conservation efforts in that Office.

Dr. Robert C. Seamans
March 17, 1976
Page 2

Based on the above, I would like to suggest that you review this organizational problem, with the purpose of determining whether the Electric Energy Systems and Energy Storage Systems work would be better off in another Office within your organization. I would appreciate receiving a reply from you in one month, so that we will have it prior to full Committee action on the ERDA authorization bill.

Sincerely yours,

Henry M. Jackson
Chairman

HMJ:ccc

APR 20 1976

Honorable Henry M. Jackson
Chairman, Committee on Interior
and Insular Affairs
United States Senate

Dear Senator Jackson:

Your letter of March 17 points out that the important programs in Electric Energy Systems and Energy Storage Systems constitute a large percentage of the funds requested in FY 1977 for Conservation, yet they are not directly related to end-use conservation objectives and hence both create an incorrect impression of the magnitude of ERDA conservation activities as well as compete for the available funding. You asked that I consider whether some organization shift of those programs would be appropriate.

While the systems programs noted do provide some support to end-use conservation activities, I believe that your observations are generally valid and relate to another matter to which we have been giving attention. As you know, electric power generation today represents 25% of the National energy usage and is expected to grow to over 40% by the end of the century. Accordingly, a major part of our energy RD&D funds are directed to new and improved electric power generation technologies and to the associated storage, transmission, and distribution capabilities. Projects with these goals are included under five of six ERDA programmatic Assistant Administrators.

Thus we find that activities toward the important goal of providing improved electric power system capabilities are spread across the ERDA organization. A recent review of those activities which will have an impact over the next 10-15 years, when the Nation must double its electric power generating capability, indicates that they are probably not receiving sufficient attention as compared to the newer but longer-term technologies.

The need for an improved organization focus on electric power systems, both short- and long-range, has thus been a matter for consideration. In reviewing the alternatives, I conclude that it would not be desirable or feasible to consolidate the various electric power efforts under a

Honorable Henry M. Jackson -2-

single Assistant Administrator in view of their quantity, variety of technologies and scientific disciplines, and the supporting interrelationships. (For example, a strong program in energy storage is vital to the activities in user conservation, solar thermal energy utilization, as well as electric power generating technologies--fossil, solar, and nuclear.) Rather, I now plan to establish an internal task force to take an integrated overview of electric systems activities within ERDA. The task force will be charged with considering appropriate short- and long-term RD&D programs, the best means of implementing a full two-way flow of information with the utilities and others, and the most desirable organizational relationships within ERDA. I expect to complete arrangements--charter, manning, and name--for this task force shortly and announce its establishment.

In this regard, then, I believe it best to leave Electric Energy Systems and Energy Storage Systems in their present organizational assignment at this time. In order to meet the concern on funding and apparent size of end-user conservation activities, I am considering a reorganization of our budget requests in future years which will segregate and hence place greater attention on the funding requests for those end-user activities.

I certainly appreciate your interest in this matter, and will be available to discuss this subject in greater detail if you deem it desirable.

Sincerely,

/S/ [illegible] Jr.

Robert C. Seamans, Jr.
Administrator

Distribution:
DA
EA/A
AMF (3)
OCR (2)
George Murray, AC

ATTACHMENT B

AUG 2 2 1978

INFORMAL NOTE

TO: Robert D. Thorne, ET

FROM: George W. Cunningham, ETN

SUBJECT: POWER DELIVERY PROGRAM

The purpose of this note is to endorse the ET-supported Electric Power Delivery Program. This endorsement is based on the fact that electric power transmission is becoming a critical technical area of concern in this country as central power stations escalate in size. This is particularly true in the nuclear industry where utilities have made commitments to large light water reactor power stations to take advantage of plant standardization and the economics of large scale plant systems. As you know, TVA has in operation three BWR units at the Browns Ferry Station, with a total installed capacity of 3300 MWe. TVA also has under construction a four unit station at Hartsville, Tennessee, which will provide 4800 MWe of capacity when available in 1983. Another example of a large nuclear station under construction is the five unit Palos Verdes Station which, when completed in 1986 by Arizona Public Service Co., will have an installed capacity of 6300 MWe.

In the more distant future, if advanced reactor concepts are introduced commercially, nonproliferation concerns may require energy park siting of complete nuclear fuel cycle facilities. These energy parks would contain a mix of LWRs and breeders, and would have transmission requirements similar to other large station concepts. Potential solutions to these electric power transmission problems which are addressed by the Electric Power Delivery Program include:

- Alternative high capacity underground transmission systems, connecting central generating plants to distant load centers situated because of cooling needs, land use issues, aesthetics, and environmental concerns.

- More effective base load management and greater systems reliability by high voltage direct current power transfer systems.

- Improved regional transmission links between systems to provide adequate emergency and economic power transfer.

Given the potential benefits of this program, I encourage the continuation of the DOE program along with industry efforts in this area. Due to tight funding limitations, however, ETN would find it impossible to provide financial support to this effort.

cc: F. F. Parry, EES

ATTACHMENT C

24 AUG 1978

MEMORANDUM

TO: Robert D. Thorne, Assistant Secretary for Energy Technology

FROM: George Fumich, Jr., Program Director for Fossil Energy

SUBJECT: NEED FOR POWER DELIVERY TECHNOLOGY

The purpose of this memorandum is to recommend continued support of the ETS Power Delivery Technology activity.

Development of improved technology for conversion of coal to electricity is a high priority ETF activity, and the main thrust of this activity is reduction of environmental impacts of coal utilization. We expect this effort to produce rapid advancement in the control of air contaminants and other environmental aspects of coal processing and combustion.

However, even with improved control technology, the utility industry can expect increasing difficulties in finding acceptable sites for new baseload powerplants. The future trend in plant siting will be toward locations remote from the load centers. Consequently, there will be an increasing need for new power transmission corridors and more effective use of existing corridors. If the technology for developing transmission corridors does not exist, our goals of increased coal utilization for power generation could be thwarted.

Therefore, I recommend that future budgets for the Power Delivery Activity be considered in view of the important role this technology will play in the expansion of coal-fired electric power generation capacity.

bcc: ETF/R
ETF (2)
ETF - M&R
FFU CHRON
FFU CRP

FFU:KBastress:jfg:8-22-78 - Ext. 64602

FFU KBastress | FFU JABelding | DETF

ATTACHMENT D

Department of Energy
Washington, D.C. 20461

July 13, 1978

MEMORANDUM FOR BOB THORNE

FROM: HAZEL ROLLINS

SUBJECT: FY 1980 BUDGET FOR ELECTRIC ENERGY SYSTEMS

I understand that in formulating your FY 1980 budget request you are considering a very substantial reduction in the Electric Energy Systems (EES) program. I am taking this opportunity to express my support for several EES initiatives that are closely related to the objectives of ERA's Office of Utility Systems.

Although continued R&D in bulk power delivery is necessary to ensure future adequacy of electric energy supply, much of this work should probably be financed by the private sector, rather than the Federal government. There are, on the other hand, several bulk power R&D areas which are appropriate Federal endeavors, since the utility industry cannot be expected to address them adequately, if at all, and since they relate directly to the national interest. These are:

1. <u>Biological Effects of Electric Fields</u>. This work supports the ERA objective of strengthening interconnections between power supply areas and power pools--in turn, enhancing capability to respond to emergencies and to utilize preferred generating facilities. Impartial R&D on bioeffects is needed to resolve the controversy over the health and safety implications of high voltage transmission lines, and private sector work will not be viewed as meeting the test of impartiality.

2. Load Management. This element of the EES program is a valuable complement to ERA rate reform programs. The EES load management activity has encouraged the utility industry to pursue hardware options, thereby giving State regulators a full range of alternatives to consider. ERA's press for greater generation efficiency through load management would be hampered without this activity, since the industry generally does not share EES's innovative outlook on load management hardware. A continued Federal presence is definitely important.

3. Controls for Large Complex Systems and Large-Scale Systems Development. ERA supports a modest level of funding for these forward-looking EES programs, which focus on emergency reactive controls and relaying methodologies for protection of systems during equipment failures and malfunctions.

4. High Voltage DC Transmission and Higher Capacity Underground Transmission. Finally, a strong R&D effort in these transmission areas is essential to ensuring future adequacy of power supply, particularly during emergencies. The major uncertainty here is what level of DOE financial support is necessary to ensure the effectiveness of transmission R&D efforts. While I defer to your judgment on this key question, I wish to emphasize the importance of getting the work done, and would point out that recent EPRI Board decisions tend to emphasize nearer-term, lower voltage transmission technologies. (The EPRI approach may well reflect an institutional aversion to controversial issues that do not directly affect near-term industry interests.)

In short, I believe that continuation of selected portions of the EES program would serve national interests, and encourage you to maintain adequate funding for these activities.

APPENDIX 2

Department of Energy
Washington, D.C. 20545

AUG 15 1978

H. Coleman, Acting Director, Div. of Central Solar Technologies
R. Black, Acting Director, Div. of Geothermal Energy
H. Marvin, Acting Director, Div. of Distributed Solar Technologies
F. Parry, Acting Director, Div. of Electric Energy Systems
G. Pezdirtz, Acting Director, Div. of Energy Storage

SYSTEM INTEGRATION OF DISPERSED GENERATION AND STORAGE

Now that the Department's solar philosophy has advanced to the point where we can see the direction and magnitude of the effort confronting us, I want to enunciate my strategy for implementing the "solar" program. This, the first of several directives outlining ETS strategy, addresses the integration of dispersed solar and storage technologies into the electric power system.

Background

Through the early years of the twentieth century, generation of electricity was done by small, widely dispersed, generation units. Some generated from coal, some from low head hydro and some from wood, but in almost all cases the plants were located close to the load and isolated electrically from each other.

Over the past 50 years several trends have taken place:

- o Generation of electricity has evolved to larger and larger generating units (economy of scale).
- o Systems have become interconnected to increase reliability and reduce cost via energy interchange.
- o Manpower costs have escalated to where it became uneconomical to keep widely dispersed manually operated small plants in operation.
- o The only storage developed was pumped hydro.

Now, as we view the future, these trends may reverse as there are new options to generate and store electricity -- in small dispersed units located throughout the electrical network, close to the load options which may be economic because of greatly increased fossil fuel costs. The electric system is vastly different, however, than at the turn of the century, or even 30 years ago. For example:

- o The entire U.S. east of the Rockies, except Texas, is now interconnected (largest such area in the world). The electric systems west of the Rockies are also interconnected.
- o Loads have increased ten-fold in 30 years, and the number of customers has doubled, resulting in an increasingly complex generation/transmission system and an expanded distribution system reaching every home and industry in the country.
- o Where normal frequency variations were expected in cycles in the 1940's, now frequency must be held and measured in thousandths of cycles. Industrial, commercial, and residential customers have come to expect and demand this accuracy.
- o Generator sizes in the 1940's were commonly 100 MVA, now they range from 500-1000 MVA.
- o Control schemes for system protection and management have evolved to accommodate the expanded system, but are not designed to integrate myriads of widely dispersed generation/storage devices.

All of these trends and patterns make dispersed generation and active use of dispersed storage much more difficult. Unless appropriate RD&D is planned and carried out on the system effects, it is clear that the electric system may not adapt to the new functions and characteristies of widely dispersed generation and storage.

<u>Discussion</u>

- o We are seeing great interest in the small scale technologies. A significant problem is the successful acceptance and integration of small generation/storage devices into the U.S. electrical network. Power system operating characteristics impose some severe constraints and requirements on the operation of individual generating sources. In recent years, even conventional plants have been subjected to new problems, such as subsynchronous resonance, due to continued growth of the national network. Both advanced control technology and intimate understanding of power system behavior are required for analysis of (a) the requirements imposed by the existing network on the design of controls for, and the subsequent operation of many new small generating plants, and (b) the problems posed by new source technologies with respect to the effective design and operation of the total system.
- o Similarly, the development of certain power related devices is critical to successful integration, especially if there are control and/or

system interaction functions -- such as power conditioners. These devices are usually a relatively small portion of the cost of the primary technology, but because of their interface/control position they must have as their primary driving force the system/equipment compatibility issue.

Strategy

As of this date, the Division of Electric Energy Systems has responsibility within ETS for the electric utility interface with respect to dispersed generation and storage. This includes:

- o Responsibility for coordinating the integration of new technologies (generation and storage) into the electrical network. The technology divisions shall involve EES at the earliest practicable time and a mutually acceptable plan shall be developed for dealing with the integration of each technology into the system. This plan shall include studies and demonstrations and designate by whom they shall be administered.

- o In similar fashion, EES shall have responsibility for developing power related, system integrating hardware common to several technologies (such as the power conditioner). The technology divisions shall make their requirements known to EES at the earliest time in order to develop a mutually agreed upon schedule for such development.

EES will take the initiative in developing integration plans for each dispersed technology, including funding requirements and source.

I would like to see mutually agreed upon plans for FY 79 this month.

Original
Signed by
Bennett Miller
Bennett Miller
Program Director for Solar, Geothermal, Electric and Storage Systems

DOE Form AD-18A
(11-77)

U.S. DEPARTMENT OF ENERGY
memorandum

DATE: July 30, 1979

REPLY TO
ATTN OF: ET-58

SUBJECT: EES Personnel Resources

TO: Martin Adams, ETS

Reference your note of July 17, 1979, directing EES to reduce its on-board strength to 18 by transferring three positions to ETS.

Upon first learning of the proposed EES personnel reduction the afternoon of April 13, 1979, I cited my memo to Bennett Miller of the same date. This memo mentions the recent loss of four technical professionals (Jim Edmonds, Steve Walldorf, Dave Mohre and Lou Krezanosky) and requests authorization to replace them. It also notes EES's expanded integration and coordination responsibilities.

At a later session with Bennett on the morning of April 23, he said that he had considered my memo but that he believed other requirements more pressing. I told him that I would spare him a reiteration of my views on the ineffectiveness of the central staff but continued to think that any cuts required should come from there, not from the program divisions.

Bennett did agree that the fuel cell program, including Len Rogers, was not considered in the reduced personnel ceiling of 18. If we retained the 4.8 MW fuel cell program management responsibility then our number would obviously be 19. If we were given responsibility for the entire fuel cell program then the EES personnel ceiling would be the subject for further negotiation.

I see no reason why this agreement between Bennett and myself should be abrogated.

F. W. Parry, Director
Division of Electric
Energy Systems

cc:
B. Miller
I. Neddow
R. Flugum
W. Feero

U.S. DEPARTMENT OF ENERGY
memorandum

DATE April 13, 1979

REPLY TO ATTN OF: ET-58

SUBJECT: EES Personnel Resources

TO: Bennett Miller, ETS

This division has contracted from a strength of 38 personnel in 1977 to 21 on board today. The damaging loss has been in technical professionals. Here we have lost thirteen of the twenty-four present in November 1977 and only been able to replace four to date. During the year and a half that this attrition has taken place, the division has taken on new significant responsibilities, notably 1) The integration from the systems point of view of new source technologies into the electrical grid, and 2) Support of ERA and others in implementation of the NEA. With almost a year's experience in developing and initiating implementation of our integration strategy, we now have a fairly clear understanding of the personnel requirements to do this job, the more demanding of the two.

Briefly, let us look at what the exercise of these responsibilities entails.

Integration from the Electric Systems viewpoint of new source and storage technologies into the grid.

Exercise of this responsibility involves coordination and interchange on a continuing basis with all the electric grid associated technologies being developed by DOE. These include: Wind, Photovoltaics, Solar Thermal, OTEC, Central Storage (CAES/UPH), dispersed storage (Batteries, thermal), Geothermal, Fossil and Nuclear. To date, effort has been concentrated on Storage, the 4.8 MW fuel cell, Wind and OTEC, with increasing attention now being paid to Photovoltaics as well. However, even this integration work is severly personnel resource limited. Initiating the highly desirable interchange with fossil (other than the 4.8 MW fuel cell) has been postponed because of want of anyone to carry it forward.

Not quite so pressing but requiring attention soon are preliminary contacts with geothermal, central solar and eventually nuclear and fusion. The decentralization of management responsibilities to the field, particularly in the solar area, has enormously complicated the performance of our system integration responsibilities, requiring considerable field as well as headquarters liaison.

Support of DOE Regulatory and Operational Responsibilities

ERA (and FERC) has important authority strengthened by the enactment of NEA with respect to emergency and economic power transfer, substitution of coal for oil, wheeling, system reliability, load management, etc. ERA has requested EES to support technology development in areas which will give them better tools with which to exercise these responsibilities.

RA's power marketing administrations, notably BPA, strongly support the power delivery and systems control elements of the EES program. C&SA has a continuing interest in that part of our R&D program which contributes to conservation (e.g. - our advanced transformer and electric motors efforts). Whereas coordination with ERA, RA, and C&SA is not in any way comparable in manpower and time requirements to implementation of the EES integration responsibility, it is not negligible and consumes a significant amount of management time (DD, Tech. Asst, Branch Chiefs). Closely related to this coordination/support responsibility is the desirability of keeping other parts of DOE (e.g. - OER) conversant with the EES program because of its relationship to most DOE activities. These responsibilities also translate into a considerable amount of time expended in an advisory role (e.g. - National Grid Study).

Neither of these responsibilities is susceptible to delegation to the field. In our considered opinion, there would be no swifter nor more conclusive way of ensuring disaster to our integration effort than to turn it over to a surrogate.

These added responsibilities have imposed a burden on the depleted EES staff which is even now evidencing itself in a diminished ability to plan and manage our R&D program as well as support the integration and NEA efforts.

The need for austerity in headquarters manning levels is clearly understood and EES is decentralizing program and project management to the field to the extent practicable. However, the division has been widely recognized as one which has a cross-cutting role, whose services and advice are needed or useful to not only the technologies being developed throughout ET but to the regulators and operators as well. This is an unique responsibility and asks for special consideration in staffing.

To perform our assigned tasks effectively, EES needs to replace the most critical recent losses. These are: In PSI - 3 Technical (Dave Mohre, Len Rogers*, Lou Krezanosky; In PD - 2 technical (Jim Edmunds, Steve Walldorf).

Recommendation That EES be authorized to recruit immediately five technical professionals.

F. F. Parry, Director
Division of Electric Energy Systems

cc: M. Adams
R. Benson
R. Flugum
W. Feero

* Assuming Rogers goes to Fossil with the 4.8 MW fuel cell program.

APPENDIX 4

ELECTRIC ENERGY SYSTEMS

1. It is important for DOE and the government in general to have an in-house capability to understand and speak to the problems and needs of the electric industry. At present, the Office of Electric Energy Systems (EES) is unique in this, having highly qualified R&D managers with utility, manufacturing and university experience in the analysis, design, planning and operation electrical power equipment and systems.

2. As new dispersed generating and storage devices become commercially available, it will be expected that each will work compatibly with the existing electric network. EES is working to provide a systems perspective in government-sponsored R&D so as to influence design of new technology devices and help insure an objective assessment of their impact on the design, protection and operation of the system. EES is supporting research aimed at providing advanced communication and control alternatives, power conditioning hardware, and analytical tools and methods so the industry can perform proper benefit and impact assessments of new technologies.

3. Land use for electric power transmission is an increasingly difficult issue. High capacity overhead and underground transmission and compact substations will provide viable options. EES has substantial underground cable research, both a.c. and d.c., key equipment development, up to 1200 kV a.c. and ± 600 kV d.c. and research on deep water cables for application down to 2500 meters.

4. Health and safety questions are holding many overhead transmission projects from completion. It is important to have an unbiased, objective group conducting rigorous R&D into the electric field effects on plants, animals and humans. EES has initiated the first and still the most comprehensive R&D, with results to be available within the next four years (depending on budgets). It is being conducted openly, under the closest public scrutiny, and will be extremely important in providing the basis for objective design and operational guidelines which will meet the health and safety requirements of society.

5. As systems become larger and more integrated, with both central and dispersed generation and storage and load management, advanced system theory is required to deal with the issues of increasing complexity and uncertainity. Analytical tools and methods are being developed by EES to help solve the development, operation, control, security and reliability concerns of the future.

6. Numerous electrical equipment areas have had almost all research done, in recent years, by foreign companies, e.g. high voltage d.c., high voltage ac circuit breakers, etc. Recent EES research in 1200 kV equipment and high capacity gas and superconducting cables is slowly counterbalancing that swing and will allow U.S. to compete more readily.

7. Research in universities draws talented students. These then are available to industry upon graduation. EES has a strong but small university research effort which already is sending dozens of young engineers to utilities and manufacturers.

8. Even though electric energy transmission is very efficient, losses on the order of 8% are still incurred between generation and consumption. Higher efficiencies can be achieved via improved lower loss magnetic materials, lower dielectric loss insulation and improved systems -- higher voltage and better controlled. All of these are in the EES program, especially for improving efficiency of motors, generators, transformers, and conductors.

(7-79)

U.S. DEPARTMENT OF ENERGY

memorandum

DATE August 13, 1980

REPLY TO ATTN OF RA-25

SUBJECT FY 1981 Organizational Personnel Ceiling

TO Rudolph Black
Acting DASRA

Resulted in DOE request of 27

In response to your request for information upon which to base a reclama to the EES FY 1981 personnel ceiling of 20, the following is provided.

Soon after her arrival last fall, Dr. Davis directed that EES accelerate its System Architecture and Integration effort as a major RA thrust for FY 1980. In response, EES developed a detailed strategy and presented this to Dr. Davis on February 6, 1980. She approved the strategy and said that she would see about getting us additional personnel to implement it. The number agreed upon was seven; this would have brought EES strength to 28. Although I reminded both Dr. Weiss and Chuck Ebbecke of this commitment several times during February and March, no action was forthcoming (attachment 1).

I continued to discuss, on at least a weekly basis, EES's need for additional personnel to accomplish its mission, finally culminating in the memo of May 16, 1980 (attachment 2). Dr. Weiss said that this provided him with adequate support to pursue the subject further with Dr. Davis. As yet, no results have been forthcoming.

In the meantime, these other pertinent actions took place.

- Dr. Davis directed me to pursue an active technical interface with the electric utility industry as contrasted with ERA's regulatory interface (February, 1980).
- Dr. Deutch issued his decisions relative to fuel cell technical and budgetary management which resulted in RA losing a ceiling to FE, even though no personnel transferred (March, 1980).
- Drs. Weiss and Savitz (CS) reached agreement on management of the storage utility applications program, transferring budgetary as well as management responsibility to EES (but no ceiling or personnel) beginning in FY 1982 (April, 1980).
- Within EES, in order to make a start at implementing the System Architecture and Integration strategy, I reassigned J. Charles Smith to head up the Integration effort. The energy storage applications program which he had managed since 1975 was reassigned to Len Rogers. (February-May, 1980)
- Chuck Ebbecke transferred a vacant (non-EES) RA ceiling to FE per the Fuel Cell directive after I told him Rogers would not go to FE. Also, I told him that Rogers was more than fully employed managing the storage applications program as well as providing advice on management of the 4.8 MW fuel cell field test at Con Ed and assembling data upon which to base the multi-megawatt phosphoric acid fuel cell industrialization plan.

- o Program planning responsibilities multiplied several fold in the past six months. The Office Director and Deputy Director are now devoting about a quarter and a half of their time respectively to this activitiy and the division director's significant amounts. This is because EES has not had a planning assistant on the staff for almost a year and a half (since Lou Krezanosky went to ERA - attachment 3).

Summarizing the personnel situation as of today and its effect on EES exercise of its assigned responsibilities:

1. The System Architecture and Integration (SA&I) effort is underway with Smith and a new hire, Skroski, newly committed to this program. However, we are neither covering the full range of new technologies nor covering those being integrated to the desired depth.

2. The Energy Storage Application sub-program and systems engineering sub-program are now seriously short of management capability because Smith and Fink's numerical replacement (Skroski) were reassigned to the SA&I effort.

3. EES has been unable to maintain its 1977-79 level of effort, must less expand its technical interface with the electric utilities because of the personnel shortage.

4. EES has less than half an engineer on the fuel cell program and retains responsibility for the fuel cell industrialization plan. Hence, it is illogical to transfer this ceiling from EES.

5. SA&I responsibilities, such as submarine cables for OTEC or inter-island ties (geothermal, wind, OTEC, etc. in Hawaii) have not been pursued vigorously due to lack of personnel.

6. Field oversight by top EES management has been almost non-existant. For example, neither the Office Director nor Deputy Director has visited any of the three principal programs under field management (Oak Ridge, Chicago or Brookhaven) within the past year.

7. EES contract oversight has declined to a serious level due to the personnel shortage. This view is strongly supported by the on-going IG audit initiated in March 1980.

8. Liaison with other DOE elements (C&S, ERA, FE, NE, OER, etc.) has been reduced.

If EES is required to manage the FY 1981 program with 20 personnel, this will accelerate the program's quality erosion underway since 1979 when EES first fell below a technical/clerical strength of 25. (administrative had been taken away in 1977). Specifically,

- o advice and assistance to other elements of DOE will be retained at a minimum level rather than expanding as requested.

- o advice and assistance to other federal agencies will not be available. If directed, as in the case of the White House carbon fibres' task, other critical activities will suffer.

- Continued at a less-than-adequate level:
  - On-going contracts review/management
  - Field inspection trips
  - Interface with industry
  - Keeping up with technology advances
  - Long range, including industrial, planning.
- Attachment 4 "Personnel Justification for EES" is included to provide further information on EES needs and recruitment priorities.

F. P. Parry, Director
Office of Electric Energy Systems
Resource Applications

Attachments

Personnel Justification for the Office of Electric Energy Systems (EES)

Due to the unique expertise of EES, on utility power systems, the Office staff is in demand to advise, review proposals, participate in plans and workshops, and in general utilize this expertise to benefit all of DOE and other federal agencies. Two years ago with an on-board strength of 38 personnel, this advisory/assistance role represented an effort equivalent to about two man-years and EES had no difficulty in accommodating it. However, with the steadily increasing emphasis on utility conservation, operational efficiency and system flexibility along with the greater emphasis on the use of renewables, requests for assistance have grown dramatically, and now represent a requirement for at least one-third of EES's total manpower effort. With the drastic, consistently-opposed reduction of EES's staff over the past two years (present authorized ceiling of 21), EES is no longer capable of meeting its responsibilities with respect to managing the congressionally mandated programs and also providing this needed advice. Accordingly, the exercise of both responsibilities has been and is suffering drastically. This advisory/ assistance role includes such recent activity as participation in:

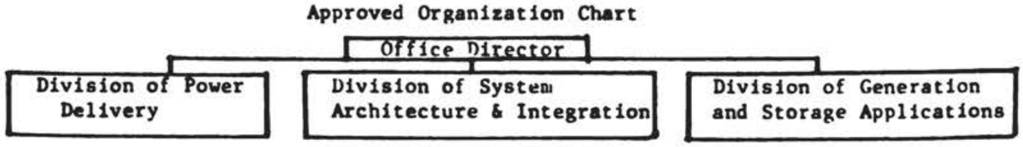
1. National grid studies
2. National Energy Transportation Study
3. Effects of Carbon Fibers on electric power systems
4. Cogeneration/Utility interface analysis
5. Utility conservation review
6. Inter-island cable ties for Hawaii
7. Source evaluation board representative for non-EES contracts (e.g.-OTEC)
8. Review of need for a national high voltage laboratory
9. Technical Base program for ERAB
10. Analysis of failure mechanisms and recommended fix for U.S. Navy transformers on nuclear carriers
11. Technical program content for Renewable Resources (DOE/CS) conference
12. Review reports for Wind, Photovoltaics, OTEC, Solar Satellite, etc. programs
13. Participate in and chair professional society committees related to electric energy systems
14. Direct current inter-island ties for southern Alaska
15. Continual interface requirements for information from Congress, other Federal agencies, and the media on electric field effects, from overhead transmission lines.
16. Active technical participation in three international energy agreements between the U.S. Government and foreign governments.

This work is folded into the job of the technical staff along with answering numerous congressional and non-DOE requests.

The workload of the Office is further complicated by the lack of staff to coordinate and prepare the numerous new budget and planning documents. As a result, the deputy office director and the division directors must utilize their time for this rather than on managing the office and divisions.

I. <u>Office of Electric Energy Systems Manning</u>

Approved Organization Chart



APPENDIX 6

DOE Form AD-18A
(12-77)

U.S. DEPARTMENT OF ENERGY

memorandum

DATE: February 15, 1980

REPLY TO ATTN OF: RA-234

SUBJECT: Report of the Fuel Cell Management Review Task Group

TO: Edwin J. Istvan
Exec. Asst. to the Asst. Secretary, RA

Thru: Stanley I. Weiss, Ra

This is to register my nonconcurrence with the report for much the same reason as the C&S nonconcurrence, as well as others which I will discuss.

I believe that the report is full of inaccuracies and subtle distortions, all of which appear designed to create a favorable environment for the Fossil Energy position outlined in the action memo to the Secretary prepared by Dr. Monsour on November 23, 1979. Neither the reclama to that memo submitted for Dr. Davis' signature but never signed nor Dr. Davis' prior memo to the Under Secretary of October 23, 1979, seem to have been seriously considered by the review task group. The issues raised by those memos were certainly not dealt with in the report.

In the interest of brevity I will not catalogue the many misconceptions which permeate the report. I will observe that the objectivity striven for by the review task group was not achieved. I will be happy to amplify this matter at any time you wish. Rather, let me address the report's flawed reasoning.

The report recommendation relies upon four principal points:

1. The need for a single fuel cell spokesman;
2. The importance of the NFCCG in development and managament of the overall fuel cell program;
3. The need to consolidate the limited technical competance in one organization; and
4. The smallness of the program.

I submit that these are not the key issues, but peripheral ones which have been over-emphasized to obscure the failure to come to grips with the basic ones under contention. Let me address these matters in turn.

1. The Need for a Single Fuel Cell Spokesman

This is not necessary or even desirable. The electric utility industry is primarily, almost exclusively, interested in the commercialization of the phosphoric acid multi-megawatt (PA) fuel cell. The electric utility industry wants to deal with one spokesman for the PA (4.8 or its derivatives) fuel cell. This should be EES since the utilities recognize that EES has provided the direction for commercialization since 1975 and through the 4.8 MW program, has established its capability for dealing with technical, implementation, and the attendant political and institutional problems associated with industrialization. For similar reasons, the spokesman for the 40 kW should be C&S, the user-oriented group. To state as a given that one spokesman is needed for the department is deceptive.

2. The Importance of the NFCCG

This group can have some marginal usefulness as an information exchange group, such as our Interagency Committee on High Voltage Electric Field Effects. However, it is foolish to propose that a committee with such diverse interests and motivations, many members of which are feeding at the DOE trough, should be developing a "national fuel cell plan." Committees are notoriously poor at such matters. The responsibility for developing a plan for commercialization of the PA fuel cell is with the major funding agency (DOE) which coordinates with the other interested principal funders, EPRI and TVA and receives input directly from the appropriate utility users group. The NFCCG is a discussion group with no established relationship or responsibility via Memoranda of Understanding or simular documentation. It develops no formal plan and receives no funding commitment or endorsement from any entity, governmental or industrial.

3. Need to Consolidate Technical Manpower

The technical manpower required to industrialize the PA fuel cell powerplant is now consolidated within EES/RA. It has the only individual in DOE with an extensive fuel cell background. It has responsibility for the integration of dispersed generators into utility systems. The transfer of personnel recommended by the report would dilute this effective management team rather than provide any sensible consolidation of manpower.

4. Smallness of Program

The program is small only if the proponent cares to make it small without concern for its viability in bringing about commercialization. The EES/RA plan for PA fuel cell industrialization, submitted as overguidance to the PPBS, totals $209 million for the period FY 81-FY 86. The EPRI plan, resulting from discussions with EES and participation in EPRI's program committee deliberations by L. J. Rogers, totals $20.5 million during the period CY 80 - CY 86. TVA plans $24 million in the period FY 80 - FY 84. I do not consider a $250 million program small.

I believe that there are three issues involved in the development of an industrialization plan and the management arrangements to implement it: application issues, industrialization issues, and management principles.

1. System Application Issues

   a. Dispersed Generators - The fuel cell needs no further technical development to demonstrate grid compatibility, service in a cogenerating mode, or the need for utility backup. However, these characteristics must be demonstrated if the system is to receive industrial acceptance.

   b. Institutional Constraints - Community concerns, regulatory impediments, and utility procedures must be identified and their effect determined if industry is to accept the fuel cell as a marketable generating option.

   c. Operational Concerns - Cost of service, availability, maintainability and durability must be determined, or suitable models promulgated, to gain utility acceptance. These issues can only be adequately dealt with by user-oriented organizations, RA and C&S.

2. System Industrialization Issues

   a. Industry Perception - Industry will avoid any new technology which suggests R&D in perpetuity. System is seen as a "black box" with an availability of spare parts. Product improvement, evidenced as availability of a replacement component, is accepted.

   b. Competitive Base - Must be encouraged and actively supported. Utilities resist purchase of sole source equipments. This issue urges RA and C&S management of the PA systems.

3. Management Principles Issue

   a. As significant as any issue is adherance to sound management principles in any industrialization plan. The recommendation violates this by removing management responsibility from the organization which has planned and managed the multimegawatt fuel cell program throughout the five years of its existence for no substantive reason. The quality of management has never been questioned and the level of resident expertise has been acknowledged by industry. As a major project, it is almost unique in DOE meeting schedule with minor cost growth. Transfer presumes personnel compatibility, smooth assumption of institutional problems, etc. It is believed that the proposed action would produce numerous problems in what is now a smooth working relationship and be viewed by industry with incredulity.

   b. Industry is encouraged by action which recognizes technical proficiency. Resolution of the current problem by transfer of budget management to technical competence would foster the confidence industry must have to support commercialization.

Recommendations

1. That budget and management authority for multimegawatt phosphoric acid systems be transferred to EES/RA.

2. That similar responsibility for 40 kW systems be assigned to C&S.

3. That RA be recognized as spokesman to the electric utility industry for multimegawatt systems; that C&S be similarly recognized by their constituency for 40 kW systems.

4. That RA provide technical support to C&S as requested relative to PA systems.

5. That FE retain responsibility for advanced fuel cell systems.

F. F. Parry, Director
Office of Electric
Energy Systems

APPENDIX A

AGENDA, WORKSHOP ON ELECTRIC ENERGY SYSTEMS RESEARCH

WORKSHOP ON ELECTRIC ENERGY SYSTEMS RESEARCH

National Academy of Sciences-National Research Council
2100 Pennsylvania Avenue, N.W.
Joseph Henry Building, Room 451
Washington, D.C.
April 24-26, 1985

AGENDA

Wednesday, April 24, 1985

7:30 a.m. REGISTRATION

8:30

- Welcoming Remarks

  Dennis F. Miller, Executive Director
  Energy Engineering Board

  Andrew F. Corry, Chairman
  Committee on Electric Energy Systems

- Keynote Address--Overview

  Craig Tedmon, General Electric

SESSION 1: SYTEMS TECHNOLOGY

9:30

- Materials
  Steiner J. Dale, Oak Ridge National Laboratory

10:15 Break

10:30

- Superconductors
  Joseph L. Smith, Jr., Massachusetts Institute of Technology

11:15

- Total System Technology: The Hawaiian Geothermal and Submarine Cable Project
  Richard O'Connell, Hawaiian Electric Company
  (Paper presented by William Bonnett, HDWC Program Manager)

12:00 Noon Lunch

SESSION 2: SYSTEMS TECHNOLOGY AND RELIABILITY

1:00 p.m.

- HVDC
  Willis F. Long, ASEA Power Systems Center

1:45

- Load Leveling
  Fritz R. Kalhammer, Electric Power Research Institute

2:30	o Electrical Components C. Bruce Damrell, Boston Edison
3:15	Break
3:30	o EMP Effects Babu K. Singaraju, Air Force Weapons Laboratory/ Nuclear Technology Communications Applications
4:15	o EMP Defenses Bronius Cikotas, Nuclear Defense Agency
6:00	Reception/Dinner
	Cosmos Club, 2121 Massachusetts Avenue, N.W.
	o Guest Speakers Benjamin Cooper and Richard Grundy Staff Members, U.S. Senate Committee on Energy and Natural Resources <u>Topic</u>: Energy Policy Making: The View from Capitol Hill

<u>Thursday, April 25, 1985</u>

<u>SESSION 3: RELIABILITY</u>

8:30 a.m.	Introductory Remarks
8:45	o Normal/Emergency Operations--Efficiency Abraham Gerber, National Economic Research Associates
9:30	o Normal/Emergency Operations--Economic Concepts Economic Trade Offs Daniel Kirshner, Environmental Defense Fund
10:15	Break
10:30	o Normal/Emergency Operations--Utility Needs and Experience Samuel C. Thomas, GPU Service Corporation (Paper presented by J. D. Gassert, Director, System Operations)
11:15	o Failure Mechanisms Robert J. Ringlee, Power Technologies, Inc.
12:00 Noon	Lunch

SESSION 4: ELECTROMAGNETIC FIELDS

1:00 p.m.	o	The Nature of Electromagnetic Fields Thomas S. Tenforde, Lawrence Berkeley Laboratory
1:45	o	Electric Field Effects Richard D. Phillips, Environmental Protection Agency
2:30		Break
2:45	o	Magnetic Field Effects Don R. Justesen, Veterans Administration (Paper presented by Robert F. Smith)
3:30	o	Research Perspectives Rene H. Males, Electric Power Research Institute
4:15	o	Role of Federal Agencies U.S. Department of Energy--Martin L. Minthorn Environmental Protection Agency--Richard D. Phillips Veterans Administration--Don R. Justesen (Paper presented by Robert F. Smith) Federal Drug Administration--Moris L. Shore

Friday, April 26, 1985

SESSION 5: PANELS

8:00 a.m.	Panel on Systems Technology
9:15	Break
9:30	Panel on Reliability
10:45	Break
11:00	Panel of Electromagnetic Fields
11:45	Break
12:00 Noon	Working Lunch
1:00 p.m.	EXECUTIVE SESSION (Closed to Public)
5:00	Adjourn

APPENDIX B

LIST OF ATTENDEES

COMMITTEE MEMBERS

Andrew F. Corry, Chairman
Retired, Boston Edison

Robert A. Bell
Consolidated Edison

David O. Carpenter
New York State Department of Health

Jose B. Cruz, Jr.
University of Illinois

John J. Dougherty
Electric Power Research Institute

Hans H. Landsberg (Retired)
Resources for the Future, Inc.

David G. Luenberger
Stanford University

Stephen A. Mallard
Public Service Electric & Gas Company

Michael T. Marron
University of Wisconsin/ONR

Allan G. Pulsipher
TVA

Z. John Stekly
Magnetic Corporation of America

Gregory S. Vassell
American Electric Power Service

Gerald Wilson
Massachusetts Institute of Technology

PRESENTERS

William A. Bonnett for
Richard O'Connell
Hawaiian Electric Company

Bronius Cikotas
Defense Nuclear Agency/RAEE

Steiner Dale
Oak Ridge National Laboratory

C. Bruce Damrell
Boston Edison

J. D. Gassert for
Samuel C. Thomas
GPU Service Corporation

Abraham Gerber
National Economic Research
Association

Fritz Kalhammer
Electric Power Research Institute

Willis F. Long
ASEA Power Systems Center

Rene H. Males
Electric Power Research Institute

Martin L. Minthorn, Jr.
U.S. Department of Energy

Richard D. Phillips
Environmental Protection Agency

Robert J. Ringlee
Power Technology Incorporated

Moris L. Shore
Federal Drug Administration

Babu K. Singaraju
Air Force Weapons Laboratory

Joseph L. Smith
Massachusetts Institute of Technology

Robert L. Smith for
Don R. Justesen
Massachusetts Institute of Technology

Craig Tedmon
General Electric

Thomas S. Tenforde
University of California

Samuel C. Thomas
GPU Service Corporation

PANELISTS

Thomas Dy Liacco
Dy Liacco Corporation

Nicholas Grant
Massachusetts Institute of Technology

Robert Lawrence (Retired)
Westinghouse Expert

Francis Fox Parry
Electric Research and Management Corp.

Moris L. Shore
Federal Drug Administration

Brendan Ware
American Electric Power Service

David White
Massachusetts Institute of Technology

John Zaborszky
Washington University