**BASIC SCIENCE AND ENERGY RESEARCH
SECTOR PROFILE**

Background for the National Energy Strategy

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ABSTRACT

This Profile report provides a general perspective on the role of basic science in the spectrum of research and development in the United States, and basic research's contributions to the goals of the National Energy Strategy (NES). It includes selected facts, figures, and analysis of strategic issues affecting the future of science in the United States. It is provided as background for people from government, the private sector, academia, and the public, who will be reviewing the NES in the coming months; and it is intended to serve as the basis for discussion of basic science issues within the context of the developing NES.

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Working drafts of the Profile were reviewed by various members of the National Laboratory Advisory Committee on the National Energy Strategy, who critiqued the material and provided additional inputs. All of these inputs are gratefully acknowledged.

EXECUTIVE SUMMARY

Basic science is one of the "foundations" of the National Energy Strategy (NES), in that it underlies virtually all the technology needed to provide the nation with safe, economical, and reliable energy for the foreseeable future. Basic science is but one part of a highly interrelated system of science and technology in which innovation and knowledge flow from basic to applied research and then to development and commercialization. This Profile conveys an appreciation of the opportunities available for basic science to enhance its contribution to our technology and energy future.

THE ROLE OF SCIENCE IN NATIONAL LIFE

Science is much more than the foundation of our energy future. It is the basis for technology progress itself, affecting all fields of endeavor, including commerce, communications, transportation, medicine, and agriculture. Economic growth depends on technological innovation, which in turn depends on continual progress in science.

Science is also the pathway to exploration and discovery of knowledge, which enhance our understanding of the universe in all its dimensions, from the quantum to the cosmological, and to the nature of life and humanity itself. A strong and enduring U.S. science enterprise is essential—both to meet the nation's energy goals by sustaining its technological base far into the future, and to enhance our understanding of global environmental changes and processes.

CHARACTERISTICS OF THE SCIENCE ENTERPRISE AND BASIC RESEARCH

Progress in science is achieved principally through research. In planning the role of research in the future of energy, we must consider the knowledge base and capability of the nation's science enterprise. The "science enterprise" is the collective effort of people at universities, private-sector research laboratories, and government research centers. The work of the enterprise is divided into three classes: basic research, applied research, and development.

In 1989, the United States expended \$132 billion on a vast range of research and development (R&D) pursuits. Of this, about 14% or \$18 billion funded basic research (National Science Foundation 1989d). This Profile provides information about this basic research: its nature, who pays for it, and who performs it.

The science enterprise is highly interconnected, in that no single field of research is totally isolated from other fields. The various fields of science and technology are mutually interdependent, as are the various institutions that pursue scientific knowledge. Moreover, the U.S. science enterprise is also highly interconnected with that of other nations, particularly in Western Europe and Japan.

The relationship between the federal government and the national science enterprise is a two-way street. Government agencies depend on a healthy and vital science enterprise to achieve their respective missions. In turn, the government provides funding and other forms of support to various elements of the nation's science community.

In 1989, the federal government expended \$62.7 billion on all types of R&D, including \$12.0 billion (almost 20%) on basic research. The U.S. Department of Energy (DOE) share was about \$5.2 billion for all R&D, of which \$1.27 billion (about 24%) was for basic research. This commitment makes DOE one of the principal mainstays of basic research in the United States and the leading sponsor of basic research in the area of physical sciences. The DOE therefore has a special responsibility for sustaining the long-term vitality of the science enterprise to perform basic research, including a commitment to ensuring that the United States maintains its position as a world science leader.

CHALLENGES TO SCIENCE AND THE ENERGY FUTURE

The science enterprise of our nation and the world is being asked to address many challenges that relate to the kind of world we will live in. The knowledge to be gained from basic research has a critical role to play in shaping this future. This Profile identifies challenges to the U.S. science enterprise in three areas:

- *addressing science issues of global significance* - Some prominent examples of the issues being addressed by the world science community include enlarging the base of fundamental knowledge about the nature of matter, energy, the universe, and living systems; understanding and controlling global and local climate change; improving human health and well-being in such areas as cancer, AIDS, heart disease, aging, and mental health; and addressing the depletion and pollution of the earth's natural resources base.
- *maintaining continued U.S. excellence in scientific research* - Our nation's ability to confront the basic science problems of our time cannot be ensured. The national science community shows signs of stress and decay. If ignored, these problems will seriously reduce scientific contributions to society and will adversely affect the U.S. competitive position in science and technology. Federal agencies whose missions depend on basic research are challenged to examine their roles in the future of the science enterprise.
- *applying the results of basic research to the NES* - Basic research has a unique and critical role to play in our nation's energy future. It is the key to an energy future involving plentiful and varied fuel resources and efficient, clean processes to use them. It is also essential for producing the new knowledge needed to understand and ameliorate the environmental impacts of energy use.

OPPORTUNITIES FOR MEETING THE CHALLENGES

Opportunities for meeting each of these challenges are identified in terms of three overriding goals for the U.S. science enterprise:

- maintain basic research to enhance the general science knowledge base and stimulate innovation
- support the nation's science enterprise to ensure its ability to maintain excellence and productivity in basic research
- focus the work of the science enterprise and its base of scientific knowledge on the goals of the NES.

Enhancing the General Science Knowledge Base

To enhance the general science knowledge base and stimulate innovation, long-term research is needed in all areas of science and technology: physics; chemistry; biological sciences; mathematical and computer sciences; atmospheric, oceanic, hydrologic and earth sciences; electrotechnology; mechanical, chemical and materials engineering; and astronomy (American Association for the Advancement of Science 1989). Fields such as behavioral sciences and materials sciences are also important. These scientific pursuits underlie our nation's ability to make progress in virtually every area of technology vital to our standard of living—to protecting the environment, to ensuring our energy future, and to enhancing our understanding of nature.

Supporting the Nation's Science Enterprise

Opportunities to continue and enhance U.S. excellence in science fall into four broad categories related to the health of the science enterprise:

- *improve the quality and stability of the technical resource base supporting basic research, including facilities, budgets, and technical manpower* - Opportunities include investing more resources (such as increased facilities or education support), stabilizing science program resources (through multiyear funding) and making available funds go further (e.g., through more scientific collaboration or more facilities and equipment sharing).
- *assess policies governing the way federal research priorities are established and basic science investments are planned* - There are opportunities to improve the criteria, data, and methods for determining science funding, for instance with wiser use of advisory panels and systematic decision aids.
- *strengthen the relationship of federal science activities to those of industry and other countries* - Opportunities include more joint research ventures or shared technical decision making, and ways to better manage intellectual property.
- *enlarge the general public's understanding and acceptance of science as an essential component of the nation's well being* - Key opportunities exist in increasing pre-college technical education and promoting more public involvement in science issues.

Focusing Basic Research on the National Energy Strategy

Opportunities for basic science to contribute to the NES can be understood in terms of the goals established for the NES:

- *ensure adequate supplies of energy at reasonable cost* - Basic knowledge will contribute to discovering, converting, and using new supplies of fossil fuels at greater conversion efficiency. In particular, additional basic knowledge about nonfossil energy sources is needed. Improved knowledge of materials and processes would mean that some renewable energy options and improved nuclear fission could contribute better in the near term. Longer-term energy options having the potential to meet the bulk of the world's energy needs, such as fusion, hydrogen, and additional renewable options, will require new knowledge gained from basic research.

- *maximize efficiency in energy production and use* - New basic knowledge is needed in broad generic areas such as combustion, heat transfer, materials, tribology, and electrochemistry. This knowledge could provide the basis for important long-term strategic changes in energy conversion and use through new basic materials conversion methods, new materials and fluids, and new chemical or biochemical processes.
- *improve environmental quality* - Fundamental information on terrestrial, atmospheric, inland water, and ocean ecosystems is essential to understand the effects of current energy and industrial emissions on those ecosystems and to anticipate future impacts. Three broad areas of environmental concern from energy system impacts are global climate change, hazardous releases and wastes, and fragile ecosystems.

If these opportunities are to be realized, policy makers and the public need to have a better understanding of how basic research fits into the NES. This Profile is a contribution to that understanding.

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1.0 INTRODUCTION

This Profile is a resource document on the role of basic science research in our nation's technology and energy future. It supports the National Energy Strategy (NES) document that is being prepared under the direction of Secretary of Energy James D. Watkins. The NES is an action plan for providing the nation with adequate supplies of competitively priced, clean energy. Basic science is one of the foundations of that plan.

Vannever Bush (1945), one of the leading thinkers on the role of science and society, writing near the end of World War II, offered the following prophetic vision on science (paraphrased):

Our future as a nation depends in large measure on the wisdom with which we bring science to bear against the problems of the coming years.

This Profile is prepared with Bush's vision in mind. Basic science forms one leg of a triad of "foundations" of the future of energy in the NES report, along with education and the transfer of technology. These are also the foundations of the future of industry, agriculture, infrastructure, and other essential human activities, all of which are interrelated. In assessing the role of basic science, all of these dimensions need to be considered.

1.1 SCOPE

This Profile addresses the role of and need for basic science from a national perspective. The U.S. Department of Energy (DOE) is represented as one key player among many, including other federal agencies and the private sector.

An overriding theme of this document is the importance of basic science as the foundation for technology. The United States needs to maintain and strengthen its basic science base. New generations of energy and environmental technology depend on fundamental scientific knowledge yet to be discovered or understood more thoroughly.

Another important message is that the federal government's relationship with the U.S. science enterprise is a two-way street. Federal agencies depend on a healthy and vital science enterprise to achieve their respective missions. In turn, the government provides major funding for basic science research programs in the nation. Accordingly, federal programs reflect a dual responsibility—to the success of their own missions and to the support of the national science enterprise. The government's role in maintaining and enhancing the health and vitality of the nation's science enterprise as a whole is examined in this Profile, with a particular focus on the role of the DOE.

1.2 SCIENCE AS THE FOUNDATION OF A TECHNOLOGY-BASED ECONOMY

Technology underlies virtually every aspect of our civilized existence—health, shelter, personal possessions, communications, transportation, work, and leisure. Technology enhances our standard of living as it creates the goods and services to meet our collective and individual needs. Technology is

interwoven with the structure of our society: our industrial and services base, and our infrastructure. Technology also hold the keys to sustaining the natural resources and environment of our technology-based civilization.

While technology is the foundation of our economy, science in turn is the foundation of technology. And while technology is so visible and tangible in our everyday lives, science often is invisible and taken for granted. For example, the Nestle Company uses the soya bean plant to produce a variety of food products that we find on our supermarket shelves. Yet very few of us are aware that these abundant and low-cost food products are the result of Nestle's investment in various basic and applied research projects, as shown in Table 1.1. For example, to detect and eliminate harmful factors in their new products, Nestle staff had to perform toxicological and metabolic studies requiring new knowledge from chemistry and physiology.

Perhaps the most dramatic and visible evidence of the results of science is the vast communications network in our lives: telephone, tele-facsimile, television, video, telecopy, computers, laser printers, digital recording, and the vast database serving everyday functions such as airline reservations and commercial credit and billing.

Table 1.1. Basic and Applied Research Underlying the Development of Soya Food Products^(a)

<u>Basic and Applied Research Activities</u>	<u>Field of Science Involved</u>
Develop and manufacture food products	Analytical chemistry Organic chemistry
Detect and eliminate harmful factors	Clinical chemistry Alimentary sciences Toxicology Nutrition and metabolism Physiology
Determine the effect of technological processes on nutrients	Physics Ultrastructure Alimentary sciences Organic technology
Evaluate the nutritional and sensory value of food formulas	Technological mathematics Sensorial metrology Experimental medicine Physiology Nutrition and metabolism

(a) Source: Salam (1987).

This complex communications network is based on fundamental scientific work in areas such as the physical and chemical properties of semiconductors, electronic signal propagation and control, basic energy transfer mechanisms, atomic lattice structure of materials, electron and photon interactions with materials, and advanced mathematical theory. Products that we often take for granted were attained after many years of difficult basic and applied research, development, and commercialization.

Other examples of the benefits of basic science are readily seen in modern medical science. Pharmaceutical products have emerged from scientific research into identifying a chemical; understanding the chemical's pharmacological behavior at the systemic, cellular, and molecular levels; and then producing the chemical for commercial use. Modern diagnostic technology uses principles that originated with basic research in physics, such as x-rays, ultrasound, electrochemistry, and electromagnetics. A recent example of medical innovation is laser technology, a product of physics laboratory research, which is now used in surgery.

In the future, science will play an even greater role in shaping our society, as the global community becomes increasingly dependent on technology that allows the expansion of communications, commerce, and economic development. This concept has been recognized; Robert Solow was awarded the 1987 Nobel prize for establishing that economic growth comes from new technology. In turn, new technology comes from basic research. The science policies of the United States, Europe, and Japan are based on this conviction; they all invest a significant fraction of their gross national product in research.

The Engineering Research Board of the National Academy of Sciences identified key research opportunities that it feels have the greatest potential for contributing to the nation's economy, security, and social well-being in several fields of multidisciplinary research (National Research Council 1987):

- bioengineering systems
- construction and structural design systems
- energy, mineral, and environmental systems
- information, communications, computation, and control systems
- manufacturing systems
- materials systems
- transportation.

Science plays a critical role in the future of each of these multidisciplinary pursuits. For example, basic knowledge about the molecular structure of the cell and its genetic behavior will be essential in achieving the principal objectives of bioengineering research: improved human health and the biosynthesis of many important substances for industrial, agricultural, and medical use.

All the applied multidisciplinary pursuits are interdependent to some degree. For example, the focus of the Profile—energy—is embedded in all of these research areas, and in many cases basic knowledge about energy will be critical to the success of the research. Reciprocally, research that is targeted at creating new energy options often will draw on the results of research in other fields.

1.3 CONTENTS OF THIS PROFILE

Chapter 2.0 introduces the major features of the U.S. science enterprise, its principal activities, and its position in the world. Chapter 3.0 provides a perspective and some statistics about the range of basic research involving the federal government, the private sector, and the university community. It explains the reasons for basic research and the roles played by each of the sectors. In Chapter 4.0, issues of global concern to science are briefly described, followed by a discussion of the obstacles the United States faces in maintaining a strong position in basic science research.

Chapter 5.0 focuses on specific areas of opportunities for science that are available to DOE and the nation's other science partners. As presented in Chapter 5.0, basic science research will contribute to the nation's energy future by working toward three targets of opportunities: enhance the base of general science knowledge and stimulate innovation, support the nation's science enterprise to ensure its ability to carry out basic research, and focus the work of the science enterprise on the goals of the NES. Chapter 6.0 contains the Profile's references, and Chapter 7.0 contains a bibliography.

Appendix A contains information on DOE's past and current role in basic science. Specifically, the appendix includes discussions of goals in basic energy research, a brief history of federal energy research, the office having primary responsibility for basic science at DOE, DOE's research facilities and university support, and representative DOE accomplishments. Appendix B lists the participants who attended the Workshop on the Basic Science Profile. Appendix C lists the members of the National Laboratory Advisory Committee on the National Energy Strategy, who reviewed the working drafts of this Profile.

2.0 THE SCIENCE ENTERPRISE IN THE UNITED STATES

The U.S. science enterprise is preeminent in the world. It is both a respected leader and a partner in the world's scientific community. The future of technology and energy depends, in part, on the basic research contributions of this national resource. This chapter introduces the major features of the U.S. science enterprise, its principal activities, and its position in the world.

2.1 THE SCIENCE ENTERPRISE AND CATEGORIES OF RESEARCH

The term "science enterprise" encompasses all institutions that support or perform scientific research, including the public sector, private organizations, and individual researchers. It also encompasses institutions that train and educate future scientists and engineers.^(a)

The science enterprise involves three broad categories of activities: basic research, applied research, and development. All three terms are used throughout this Profile. However, the primary emphasis is on basic research and its place in the R&D spectrum.

The National Science Foundation (1989a) defines the three categories of research as follows:

- **Basic Research:** The objective . . . is to gain fuller knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind.
- **Applied Research:** The objective . . . is to gain knowledge or understanding necessary for determining the means by which a recognized and specific need may be met.
- **Development:** Systematic use of the knowledge or understanding gained from research, directed toward the production of useful materials, devices, systems, or methods, including the design and development of prototypes and processes.

The lines between these three categories of research are sometimes blurred. For example, basic research is defined as "not having specific applications in mind." However its boundary with applied research is not always clear. Often, a decision to fund basic research is "targeted" or "directed" toward an expected useful outcome. Figure 2.1 illustrates the difference between general or "undirected" and strategic or "directed" approaches to basic research. While both approaches add to the pool of scientific knowledge, general basic research is driven mainly by curiosity and its principal effect is new science knowledge, which in turn will stimulate more basic research. Historically, general basic research has also produced important opportunities for applied R&D. In contrast, strategic basic research is driven by basic knowledge needs in support of technical programs or policies. While strategic basic research also adds significantly to new science knowledge, the expectation is that it will principally lead to applied R&D. Both approaches to basic research use the same methods, tools, and skills, and both are essential to ensure diversity and a healthy science enterprise.

(a) From *Education: Investing in Human Resources*, a Profile paper (working draft).

Figure 2.1. General and Strategic Basic Research

While much of basic research appears to be highly specialized and fragmented, the various fields are highly interrelated and interdependent. For example, in the field of physics, a recent study by the National Academy of Sciences (1986) reports:

Because the principles of physics serve as a foundation for other sciences, new discoveries in physics frequently stimulate research in associated sciences. In turn, problems of other sciences can present physicists with profound challenges.

Understanding the interdependence among the fields of science and among basic, applied, and development activities is essential to sound planning of the role of R&D in our energy future.

2.2 THE U.S. INVESTMENT IN RESEARCH AND DEVELOPMENT

In 1989, the total national investment for all categories and fields of R&D was over \$132 billion. This investment is a significant proportion of all U.S. resources, amounting to about 2.6% of our gross national product (GNP). The national R&D effort employs over 800,000 scientists and engineers.

The commitment to R&D has remained consistent in recent time, as Figure 2.2 shows. Expenditures for R&D grew from under \$30 billion in 1970 to over \$132 billion in 1989, an increase of about 450%. However, the figure shows that after adjusting for inflation, the real increase in R&D expenditures over the 20-year period has only been about 70%, keeping pace with the growth in real GNP. In the same period, basic research grew from \$3.75 billion to \$18.57 billion, an increase of 523% in current dollars

(a) The basic research component, in billions \$.

Figure 2.2. Growth in R&D Funding (billions \$)^(b)

(b) Source: National Science Foundation (1989d).

and 172% in constant dollars. Therefore, the investment in basic research has been growing faster than the investment in total R&D (National Science Foundation 1989d).

Figure 2.3 provides an overview of some of the characteristics of this \$132 billion R&D effort. As the figure shows, government and industry provide most of the R&D funds in about equal proportion (47% and 48%, respectively). However, the nation depends on industry to carry out almost three-fourths (72%) of the work. Correspondingly, industry employs a similarly high proportion of the nation's scientists and engineers, about 74%.

Figure 2.3 also shows that about two-thirds of the total national R&D effort is devoted to development, with the remaining one-third divided between basic and applied research. Table 2.1 gives a more detailed breakdown of funding for R&D by source and by category of research (National Science Foundation 1989d). As the table shows, the federal government is the largest source of funding for basic research. Most university and college funding is also earmarked for basic research. Private industry is the largest source of funding for both applied and developmental research, with the federal government following closely behind (National Science Foundation 1989d).

In addition to funding R&D, the federal government also helps to maintain the national research infrastructure (equipment and facilities). That infrastructure not only includes instruments such as electron

- Federal Government
- Industry
- Universities and Colleges
- Nonprofit Institutions
- FFRDC^(b)

- (a) Fulltime Equivalents.
- (b) Federally Funded R&D centers administered by universities and colleges.
- (c) Source: National Science Foundation (1989d).
- (d) Totals may not sum because of independent rounding.
- (e) Expenditures for R&D are an estimated \$132.4 billion (1989).

Figure 2.3. The National R&D Effort^(c,d,e)

Table 2.1. Sources of Funds for R&D by Type of Research^(a) (1989, \$ millions)

	<u>Basic</u>	<u>Applied</u>	<u>Development</u>	<u>Total</u>
Federal	12,020	11,060	39,620	62,700
Industry	3,305	14,455	46,275	64,035
Universities and Colleges	2,310	1,200	290	3,800
Other Nonprofit	<u>935</u>	<u>585</u>	<u>295</u>	<u>1,815</u>
Total	18,570	27,300	86,480	132,350

(a) Source: National Science Foundation (1989d).

microscopes, but also whole facilities such as linear accelerators or synchrotron light sources (referred to as "R&D plant"). Table 2.2 shows the funding by agency for R&D plant (National Science Foundation 1989a). DOE provides the greatest amount of funding for R&D plant, \$1.1 billion out of a total \$2.4 billion designated for FY 1990. (More details about DOE's role are provided in Chapter 3.)

Table 2.2. Federal Obligations for R&D Plant, FY 1990 (in millions \$)^(a,b)

<u>Agency and Subdivision</u>	<u>For R&D Plant</u>
U.S. Department of Energy	1,102
National Aeronautics and Space Administration	589
Department of Defense	516
Other Federal	88
National Science Foundation	86
Department of Agriculture	58
Total	2,440

(a) Source: National Science Foundation (1989a).

(b) Totals do not sum because of independent rounding.

In all, basic research represents only 14% of all dollars spent for R&D. However, both applied and developmental research depends on the results of basic research. Therefore, the contribution of basic research cannot be measured in terms of dollars alone. Section 3.0 of this Profile will expand on the role and contribution of basic research in the science enterprise.

2.3 THE U.S. WORLD POSITION IN SCIENCE

The United States has enjoyed a position of leadership in science during most of the twentieth century. This leadership position has placed the United States at the forefront of technological advancements during World War II and in subsequent decades, which in turn has contributed to sustained economic growth and to one of the highest standards of living in the world. The U.S. leadership position can be demonstrated in at least three ways: Nobel Prizes for science and medicine, citations of scientific literature, and funding for research.

The United States has claimed more Nobel Prizes in science and medicine than any other country. The annual Nobel Prizes in science and medicine are a recognition of breakthrough discoveries in the fields of physics, chemistry, physiology, and medicine. In all, U.S. scientists have claimed 102 out of 244 prizes in science and medicine since the first award in 1901.^(a) Since 1936, the United States has won or shared 60% of all prizes in these categories.

The United States contributes a large share of the world's scientific literature, over one-third of all articles in 1984. Figure 2.4 shows the share of scientific literature (percentage of articles written by country).

(a) Includes prizes awarded to U.S. citizens, U.S. citizens with dual citizenship, and joint awards with foreign scientists (*World Almanac* 1990).

Figure 2.4. Share of Scientific Literature, 1984^(a)

(a) Source: National Science Foundation (1988).

U.S. scientific leadership is also reflected by the number of articles that are subsequently cited in the work of other researchers. For every 100 articles written by United States researchers, 137 citations were received. This figure exceeds that of any other country (National Science Foundation 1988).

The United States is the world leader in total R&D expenditures and funding for basic research. Table 2.3 shows total expenditures for nondefense-related research for the United States and four other scientifically advanced countries. The table also shows the percentage of total R&D expenditures devoted to basic research. The United States outspends these countries, although other countries commit a larger proportion of their budget to basic research. Also, as a percentage of GNP, the United States is last among these countries in funding nondefense-related R&D (National Science Foundation 1988). This position raises concerns about the U.S.'s long-term competitive position in science and technology.

These indicators show that the United States has been in the forefront of world science. Maintaining a leadership position in both science and technology has implications for the nation's continued economic strength, defense posture, and ability to influence issues of global concern. However, these measures of past accomplishments do not ensure future success.

As the following chapters will show, the health and vitality of the science enterprise and its ability to produce the basic research needed for the nation's energy future cannot be taken for granted. The next chapter presents a more detailed review of basic research within the U.S. science enterprise. This review will help in understanding the challenges to continued excellence in science and to the options for meeting those challenges, which are described in the final two chapters.

Table 2.3. Estimated Nondefense R&D Expenditures and Percentages for Basic Research
(constant 1982 U.S. \$, billions)^(a)

<u>Expenditures</u>	<u>France</u>	<u>West Germany</u>	<u>Japan</u>	<u>United Kingdom</u>	<u>United States</u>
1975	6.6	11.2	16.6	7.2	43.6
1980	7.6	14.5	23.0	N/A ^(b)	55.8
1985	10.5	17.6	35.8	9.2	66.6
<u>Percentage of Non- defense R&D for Basic Research</u>					
1975	21	26	15	14	13
1980	21	21	15	13	13
1985	20	18	13	N/A ^(b)	12
<u>Percentage of Non- defense R&D of Gross National Product</u>					
	1.8	2.6	2.8	1.8	1.7

(a) Source: National Science Foundation (1988).

(b) Not available.

3.0 BASIC SCIENCE RESEARCH IN THE UNITED STATES

This chapter describes the range of basic research involving the federal government, the private sector, and the university community. It explains the reasons for basic research and the roles each sector plays. In developing options for basic research contributions to our energy future, we must understand the respective strengths, resources, preferences, and weaknesses of each of these sectors.

Within the federal sector, the DOE is the leading source of basic research funding in energy and the physical sciences. Because of DOE's critical role, this chapter briefly describes the programs, capabilities, and accomplishments of DOE-sponsored basic research. Appendix A provides further details for reference.

3.1 THE RATIONALE FOR INVESTING IN BASIC RESEARCH

The federal government, private sector, and universities and colleges invest and participate in R&D to realize benefits to society in areas such as health, environment, energy, transportation, communications, and national defense. While R&D funding is heavily slanted towards "development," basic and applied research is considered essential components of a balanced R&D investment portfolio. Specifically, the role of basic research is to provide:

- a constantly evolving understanding of the universe, the earth, living systems, and the fundamental nature of matter and energy
- steady increases in knowledge that allow existing technology to be continuously and incrementally improved
- scientific breakthroughs that allow entirely new areas of technology to be developed
- methods of observation and insight into the nature of scientific inquiry
- human skills and capabilities in all of the above, which contribute to U.S. international leadership and preeminence in science and technology.

While the science community recognizes the benefits of basic research, these benefits are difficult to defend in a rigorous manner. John F. Ahearne (1985), while at Resources for the Future, wrote:

Fundamentally, support for basic research is subjective, based on the conclusion that basic research leads to important public benefits—in ideas generated, people trained, and intellectually stimulating environments provided

Harvey Brooks (1985) of Harvard University admonishes against trying to justify research in terms of economic payoff:

There are dangers in basing policy on simplistic notions of direct economic payoff from specific areas of research because the origins of applications are buried so deeply within the whole context of science. Often, rediscovering them would require almost as much research as was involved in the original science.

Therefore, R&D policy and decision makers depend on a thorough knowledge of basic research opportunities and often rely on the science peer community for advice on investments. Part of the investment is committed to supporting general basic research, whose motives are principally new understandings of nature with no specific downstream application in mind. Another part of the national basic research portfolio, strategic basic research, is aimed at producing new scientific knowledge that can be applied later, although neither the specific knowledge nor the manner of application can be predicted. Both dimensions of basic research activity are essential to ensuring a diversified and innovative science enterprise.

3.2 THE U.S. INVESTMENT IN BASIC RESEARCH

This section provides an overview of the major sources of funding and performers of basic research. Then the role of each major sector--federal, private industry, and universities and colleges--is discussed. Each provides a distinctly different emphasis in choice of basic research areas.

3.2.1 Funding and Performance of Basic Research

Of the \$132 billion expended on U.S. R&D in 1989, \$18.6 billion (14%) was for basic research. Figure 3.1 focuses on this basic research component and compares participation by source of funding and by performer of the research. The federal government is the largest source, accounting for about 65% of total basic research funding. The university and college sector performs over half of all basic research. If university-administered federally funded R&D centers (FFRDCs)^(a) are included, the academic community receives nearly 63% of all basic research dollars (National Science Foundation 1989d).

3.2.2 The Role of the Federal Sector in Basic Research

Federal funding for basic research is supported by a host of departments and agencies. Table 3.1 shows federal funding for basic research by department and agency, and by discipline of science. Almost 50% of all federal basic research support is designated for the life sciences, with the Department of Health and Human Services (HHS) as the leading federal investor. The next largest field for federal funding is physical sciences (24% of total funding), with the DOE as the leading investor (National Science Foundation 1989d).

(a) The National Science Foundation (1987) distinguishes among research programs administered directly by the federal government (e.g., the National Institute of Science and Technology), those administered by private sector organizations (e.g., Oak Ridge National Laboratory), and those administered by universities. See Tables A.2 and A.3 in Appendix A for examples of corporate and university administrators of DOE-sponsored laboratories.

(a) University - administered, federally funded research and development centers

Figure 3.1. Basic Research by Source of Funding and by Performer of Research (percentage, 1989)^(a,b)

(a) Source of funding (millions \$): federal government—12,020; industry—3,305; universities and colleges—2,310; and other nonprofit—935. Performer of research (millions \$): federal government—2,270; U&C FFRDCs—2,250; industry—3,150; universities and colleges—9,500; and other nonprofit—1,400.
(b) Source: National Science Foundation (1989d).

3.2.3 The Role of the Private Sector in Basic Research

The private sector invested \$95.4 billion in R&D in 1989. Of that total, only about \$3.1 billion or a little under 5% is classified as "basic." While data are not available for 1989, Table 3.2 shows the approximate distribution of total private sector R&D by product field using 1983 and 1986 data. Most of this research is conducted in just four product fields: transportation equipment, electrical equipment, machinery, and chemicals and allied products. Data on the distribution of basic research are not available (National Science Foundation 1987).

Table 3.3 shows private industry's performance of basic research by field of science (National Science Foundation 1987). A breakdown by field of science for each product field would be useful; however, obtaining reliable and detailed data on how industry invests its basic research dollars is difficult. Much of the basic work is highly proprietary, and federal surveys such as those of the National Science Foundation publish only the broadest statistical results. However, data from 1983 indicate that 75% of the private sector basic research is in the physical sciences and in basic engineering, a sharp contrast to the federal commitment of 34% (Table 3.1).

Industrial basic research is distinguished from government basic research in that industry *does* expect a commercial return on its investment from its R&D portfolio as a whole. However, industry recognizes that the payoff from an individual high-risk, long-term (i.e., basic research) project may be hard to realize. While "long-term" to industry may be five to ten years, the government horizon may span several decades.

Table 3.1. Federal Obligations for Basic Research, by Agency and Field of Science/Engineering, FY 1990 (millions \$)^(a)

Agency and Subdivision	Total	Life Sciences	Psychology	Physical Sciences	Environmental Science	Mathematics and Computer	Engineering	Social Sciences	Other Sciences NEC ^(b)
Total, All Agencies	11,300^(c)	5,199	218	2,754	1,048	369	1,107	119	308
U.S. Departments									
Agriculture	512	439	0.1	34	5	5	11	19	-
Commerce	31	-	0.1	23	4	1	4	-	-
Defense	964	104	43	180	147	113	376	-	3
Energy	1,394	109	-	1,087	39	45	112	-	1
Health & Human Services	4,754	4,125	156	117	-	12	61	94	119
Interior	129	4	-	9	84	2	29	-	-
Veterans Affairs	16	15	1	-	-	-	-	-	-
Environmental Protection Agency	76	28	-	15	20	-	13	-	-
National Aeronautics & Space Administration	1,462	40	3	816	276	21	297	0.2	8
National Science Foundation	1,754	301	15	454	465	137	204	40	108

(a) Source: National Science Foundation (1989d).

(b) Not Elsewhere Classified.

(c) The \$11.3 billion total in Table 3.1 is for FY 1990 versus the reported figure of \$12.0 billion in Figure 3.1 for FY 1989. The difference in funding does not indicate a decline in basic research funding from FY 1989 to FY 1990. Instead, the difference reflects differences in the methods and classification used.

3.2.4 The Role of Universities and Colleges in Basic Research

The connection between basic research and the university sector in the United States has special significance. Basic research programs support the nation's science and technology apprenticeships in the form of graduate degree programs and post-doctoral specialty training. Basic research is the training and practice ground for the scientists on whom the nation depends for all of the R&D work accomplished, and beyond R&D, for managing technology in industry and the private sector. Therefore, basic research at universities has an importance that transcends the actual uses made of its results.

Most funding for basic research goes to universities and colleges directly from federal agencies or in association with the university-administered, federally funded R&D centers. Table 3.4 shows the distribution of this research into the principle science/engineering fields. Life sciences is the dominant field, receiving 55% of the funding; followed distantly by basic engineering research, receiving 16%; and physical sciences, receiving 12% (National Science Foundation 1987).

Table 3.2. Private Sector Distribution of Total R&D Expenditures by Product Field^(a,b)

<u>Product Field</u>	<u>Percentage</u>
Transportation equipment (includes spacecraft missiles, and aviation)	32.7 ^(c)
Electrical equipment (includes communications and electronic components)	22.4 ^(c)
Machinery (includes computers and other office machinery)	13.3 ^(c)
Chemicals and allied products (includes drugs and plastics)	11.2 ^(c)
Professional and scientific instruments	6.7 ^(c)
Materials (metals, rubber, paper, lumber, wood, stone, clay and glass combined)	5.0 ^(d)
Petroleum refining	2.0 ^(d)
Food and kindred products	2.0 ^(d)
All other categories	4.7 ^(c)
Total	100

(a) Source: National Science Foundation (1987).

(b) Denotes estimated percentage based on data for development expenditures only.

(c) Distributions calculated based on most currently available data (1983).

(d) Distributions calculated based on most currently available data (1986).

Table 3.3. Estimated Basic Research Performed by Industry by Field of Science, 1983^(a,b)

	<u>Percentage of Total Funding</u>
Physical Sciences	43
Basic Engineering	32
Life Sciences	13
Other Sciences	9
Mathematics	1
Environmental Sciences	1
Total	100

(a) Source: National Science Foundation (1987).

(b) Percentages do not add to 100 because of rounding.

Table 3.4. Estimated Basic Research Performed by Universities and Colleges by Field of Science, 1986^(a)

	<u>Percentage^(b)</u>
Life Sciences	55
Engineering	16
Physical Sciences	12
Environmental Sciences	7
Social Sciences	4
Computer Sciences	3
Other Sciences	2
Psychology	1
Mathematical Sciences	1
Total	100

(a) Source: National Science Foundation (1987).

(b) Percentages do not add to 100 because of rounding.

3.3 THE ROLE OF THE DOE IN BASIC SCIENCE RESEARCH

DOE has the primary responsibility for basic research in energy but shares this responsibility with other federal agencies, universities, and the private sector. Basic research supports DOE's overall mission and also has benefits that extend beyond the energy area, in health, infrastructure, and the advancement of scientific knowledge in general.

The following subsections briefly describe DOE's goals in basic energy research, its history, the office having primary responsibility for basic science, DOE's research facilities and university support, and representative DOE accomplishments. Each topic is discussed in greater detail in Appendix A.

3.3.1 The Goals and Mission of Basic Energy Research

The particular goals of DOE civilian energy research have been stated by the Energy Research Advisory Board (DOE 1985):

- provide a strong array of economically attractive supply and efficient end-use options to help satisfy the nation's unpredictable energy future
- conduct research to identify and mitigate the impact of energy production and use on health, safety, and the environment

- advance fundamental scientific knowledge and education in the disciplines that DOE supports.

Basic research in DOE is conducted in many areas that are linked to energy problems and issues. For example, the materials used in energy production, transmission, and conversion technologies are often the critical constraints on more energy-efficient operation. Materials research today includes very basic studies of atomic and molecular structure, and of material interactions with light and other electromagnetic excitation sources. Developing fundamentally new energy sources such as fusion requires knowledge of plasma physics, hot gas radiation, statistical mechanics, and surface phenomena. Predicting the environmental impacts of energy use includes determining the migration of chemical and physical agents through various environmental pathways and their effects on natural systems. The very nature of these research topics falls under basic science.

3.3.2 History of Federal Energy Research

Federal funding for basic research on a large scale essentially began in the 1940s with efforts to support the war effort, including the development of an atomic bomb (the Manhattan Project). The first Atomic Energy Act was passed in 1946, establishing the Atomic Energy Commission (AEC). The Act authorized the AEC to conduct R&D related to using fissionable and radioactive material for medical, biological, and health purposes and to conduct research on the health effects of radiation to establish health guidelines.

Most federal energy research from the 1940s through the 1960s can be characterized as long-term basic research in nuclear technology. It was not until the early 1970s that the AEC began to expand its energy research program to include other technologies. The Energy Research and Development Administration (ERDA) was established in 1974 and assumed the research functions of the AEC while expanding into new areas, including solar, renewables, fossil, and energy conservation technologies.

The DOE was established October 1, 1977, consolidating all major federal energy activities, including basic research. Energy research in the 1980s saw a re-emergence of the emphasis towards long-term, high-risk, basic research. The character of basic energy research now encompasses a great variety of energy and environmental science, from high energy and nuclear physics to global climate change research.

3.3.3 Office of Energy Research Programs

The DOE's Office of Energy Research (ER) has the primary responsibility for basic research at DOE. Total funding for ER in FY 1989 was approximately \$2.2 billion^(a) (see Table 3.5). Basic research within ER is organized into five major program areas: 1) High Energy and Nuclear Physics, 2) Basic Energy Sciences, 3) Fusion Energy, 4) Health and Environmental Research, and 5) Superconducting Super Collider. See Appendix A for a description of these program offices.

3.3.4 Research Facilities and University Support

DOE-owned laboratories include large multiprogram labs and a host of smaller single-program labs. Most of these laboratories house user facilities that sometimes have unique capabilities. User facilities

(a) U.S. Department of Energy. 1990 (Draft). *Programs of the Office of Energy Research*. U.S. Department of Energy, Washington, D.C.

Table 3.5. Office of Energy Research, FY 1989 Appropriations^(a)

<u>Program Area</u>	<u>Funding (\$ millions)</u>
High Energy and Nuclear Physics	823.5
Basic Energy Sciences	549.3
Fusion Energy	350.7
Health and Environmental Research	257.5
Superconducting Super Collider	98.6
Oversight and Advisory Activities	86.2
Total	2,165.8

(a) U.S. Department of Energy. 1990 (Draft). *Programs of the Office of Energy Research*. U.S. Department of Energy, Washington, D.C.

are available to all qualified U.S. researchers based on the merit of the proposed research. DOE currently provides about \$400 million in direct support of university research, with nearly 90% of this support coming through ER (see Table 3.6).

3.3.5 Representative DOE Basic Research Accomplishments

Basic research programs in DOE (and its predecessor agencies) have a solid record of accomplishments and have made several important contributions to new scientific knowledge. Some selected examples are briefly described below, and all but the last two are described in more detail in Appendix A:

- Molecular Beam Application - Using lasers, Nobel Laureate Y. T. Lee at Lawrence Berkeley Laboratory causes alteration of benzene molecules with far-reaching implications for chemistry.
- Synthesis of Silicon Carbide - Ames Laboratory makes it possible to produce silicon carbide in the form of fibers.
- X-Ray Laser Microscope - Princeton Plasma Physics Laboratory has developed this new tool, which is capable of revealing the details of biological systems.
- Advance in Imaging of Material Defects - Developed at Oak Ridge National Laboratory, this process helps perfect superconductor materials.
- Thermally Unstable Complexants - This new class of chemicals developed at Argonne National Laboratory has potential for hazardous waste cleanup applications.
- Mathematics of Crack Propagation - Oak Ridge National Laboratory has advanced the state of the art.

Table 3.6. DOE Direct University R&D Funding by Research Program (\$ millions)^(a)

<u>Office</u>	<u>FY 1988 Actual</u>	<u>FY 1989 Actual</u>	<u>FY 1990 Estimate</u>	<u>FY 1991 Estimate</u>
Energy Research	446.5	423.2	388.5	374.3
Other DOE	87.2	83.9	80.7	79.6
Subtotal	533.7	507.1	469.2	453.9
Congress Mandated ^(b)	-135	-92	-20	N/A ^(c)
DOE Based on Annual Budget Request	399	415	449	454

(a) Source: Obtained from a DOE Comptroller crosscut table on university R&D FY91 (January 1990 internal document).

(b) Congress has voted a variable amount each year to fund specific facilities and projects for DOE's administration beyond DOE's annual budget request. These additional funds are then included in the summary of "actual" program expenditures. Since 1988, DOE and its Office of Energy Research have submitted incrementally increasing budget requests for university R&D. This pattern of increase is shown on the bottom line, most of which was managed by the Office of Energy Research.

(c) Not available.

-
- **Chemical Separations and Blood Serum** - DOE was a supporter of Nobel Prize-winning research that led to the development of artificially synthesized molecules, which now have clinical applications for analyzing blood serum.
 - **Ozone Depletion** - Research co-sponsored by DOE led to development of a theory that helps to explain the depletion of stratospheric ozone associated with the Antarctic "ozone hole."
 - **Subsurface Microbiology** - DOE investigation of environmental pathways of energy-related agents has significantly increased knowledge of subsurface microbial communities. This new knowledge has changed current thinking on the effects of microbial communities on chemical contaminant stability and mobility.
 - **Nuclear Medicine** - DOE's research and work in producing and distributing radioisotopes have been a major impetus in developing nuclear medicine for diagnosis and treatment.
 - **Water Quality and Ocean Productivity** - DOE's Brookhaven National Laboratory developed a series of instruments for monitoring water quality in regions subjected to chemical stress.
 - **Development of Supercomputers** - DOE has been a leader in developing supercomputers for 45 years and has the largest scientific computing center in the world at Los Alamos National Laboratory.

- **Near-Term Benefits of Fusion** - Meeting the technological requirements of fusion has led to advances in fields ranging from microwave technology, to materials science, and applied superconductivity. In the United States, the fusion program is exclusively sponsored by DOE.
- **Commercial Photovoltaic Technology** - DOE-supported basic research has contributed to the development of a worldwide photovoltaic energy enterprise, encompassing power systems for remote rural sites in applications such as communications, refrigeration, and water pumping.
- **Civilian Nuclear Reactors** - DOE and its predecessor agencies carried out the basic research that has enabled the development of the worldwide nuclear power enterprise.

These examples of DOE-sponsored accomplishments illustrate our nation's ability to focus government, university, and industry scientific capability in problems of national and global significance. The following chapter outlines the global issues and challenges confronting the U.S. science enterprise in the environmental, energy resource, and other areas.

4.0 CHALLENGES TO SCIENCE AND THE ENERGY FUTURE

The U.S. science enterprise shares a global concern for the long-term quality of the human environment and for the ability of the earth to continue to provide the energy and other resources needed to sustain an acceptable standard of living. Currently available technology cannot provide this assurance over the long-term. New scientific knowledge, conceptual breakthroughs, and innovation are needed as we approach the twenty-first century. This awareness poses the following challenges to the basic science community:

- provide the scientific knowledge needed to ensure the future of our technology-based society and to solve problems that ultimately relate to the survivability of the human race
- ensure that the U.S. science enterprise has the resources, competency, commitment, and vision needed to address these national and global problems
- in particular, focus the resources of the U.S. science enterprise on problems related to the future of energy in the United States and the world, recognizing that energy and all of the other global problems are interrelated.

These challenges are introduced in the following sections, and opportunities for meeting the challenges are provided in Chapter 5.

4.1 SCIENCE ISSUES OF GLOBAL SIGNIFICANCE

Science has been the foundation of our technologically advanced society and has added immeasurably to human welfare, as discussed in Chapter 1. However, science and technology have also created new threats and risks to human welfare and to the global environment, on which civilization depends.

Science challenges for the twenty-first century therefore include continuing the progress in technology that enhances the quality of life, while reducing or eliminating the resulting problems from those technologies that threaten that quality of life. For example, emissions from smokestacks and exhaust pipes contribute to regional pollution, and growing concentrations of atmospheric CO₂ from the burning of fossil fuels may be contributing to global warming. The problem of waste disposal is now reaching critical levels. Moreover, the age-old problems of adequate food supply, disease prevention and treatment, reliable and cost-effective energy sources, and maintenance of the capital infrastructure (e.g., roads, buildings, and machinery) need to be more effectively addressed.

The discovery and use of energy are intertwined with many of these issues. The technologies needed to fully address current and future problems do not yet exist and will only result from more basic science research. The following issues have been identified as posing a continuing challenge to the national science enterprise.

- *Fundamental Knowledge of Nature* - Further progress is needed in developing a fundamental understanding of living systems, matter, energy, and the universe. While such knowledge alone may not directly solve critical social problems, that knowledge historically has led to major innovations that

could not have been predicted or anticipated. Moreover, investing in fundamental research strengthens the U.S. leadership in the world science community and indirectly contributes to U.S. technological leadership.

- *Global and Local Environmental Change* - Global and local environmental and climate changes need to be better understood and predicted. Worldwide patterns of energy technology and chemical releases into the environment are loading the atmosphere with carbon dioxide, oxides of sulfur and nitrogen, chlorinated fluorocarbons, and other chemicals. Data suggest that current and projected emission levels have the potential to adversely affect the climate patterns of the earth by depleting the ozone, increasing infrared ray penetration, and raising the average temperature of the atmosphere. At the regional and local levels, microclimatic effects are altering temperature, rainfall, and the pH of lakes and rivers, and are damaging forest, agricultural, fishery, and wildlife resources.
- *Human Health and Well-Being* - While science has contributed significantly to increased human life expectancy, challenges to human health and well-being continue to confront the science community. Heart disease, cancer, genetic disease, infectious disease (now including AIDS), and the effects of aging still need to be researched further. Challenges to mental health and social behavior stem from high-density urban populations.
- *Depletion and Pollution of the Natural Resource Base* - The high standard of living in the modern world imposes several stresses on the natural resource base of the earth, the oceans, and the atmosphere. Farmlands, forests, fisheries, mineral wealth, water supplies, and clean air are being depleted and polluted. Current patterns of energy use are partly responsible.
- *Other Challenges* - Additional scientific knowledge will play a crucial role in many other challenges confronting modern civilization, such as deterioration of the infrastructure (roads, bridges, etc.), overpopulation, nuclear proliferation, natural hazards (floods, droughts, hurricanes, earthquakes, forest fires) and the continuing devastation and threat of wars, particularly in certain Third-World regions.

Meeting these challenges will require application of the full range of scientific knowledge currently available and of knowledge yet to be revealed. One of the keys to success is the health of the science enterprise, as discussed in the following section.

4.2 CHALLENGES TO THE EXCELLENCE OF THE U.S. RESEARCH ENTERPRISE

The United States currently faces serious challenges to maintaining its tradition of excellence in basic research. With expanding research needs and rising costs, science in the United States shows increasing signs of institutional stress. U.S. global science leadership is challenged, in part because of other nations' increased science prowess and investments. However, domestic pressures that threaten the continued excellence of the enterprise are of principal concern. The nation's science infrastructure is experiencing some decay, and science resources are limited.

All of the challenges discussed in this section are relevant to the issue of how U.S. science policy as a whole is implemented. This is analogous to the issue of how the economy itself is managed in a free-enterprise society. In managing our society's economy, policy makers develop principles, regulations, incentives, and supports to encourage the best economic performance. This same philosophy needs to be applied to the performance of the nation's science enterprise. Techniques for sound management, consistent with traditional American values, need to be explored and adapted to changing conditions.

The following issues represent different facets of the challenge to manage our nation's science enterprise more effectively:

- high costs of research and the ability to maintain an adequate base of research activities
- balancing of research priorities
- an adequate supply of scientists and engineers
- access to the growing knowledge base for the science and policy communities
- cooperation and coordination of multidisciplinary and multi-institutional groups in solving key problems of global importance
- acceleration of transfer of research results
- the public understanding and perception of science.

These challenges are not independent; strategies for meeting one challenge must be integrated with the others. Each is discussed in the following subsections.

4.2.1 Costs of Basic Research and Adequacy of the Research Base

The frontiers of knowledge have become extremely broad and sophisticated. A major challenge to the nation's basic research community is meeting the escalating costs of conducting state-of-the-art science. Cutting-edge research increasingly relies on complex, expensive equipment, tools, and facilities. Modern basic research rarely involves the efforts of only one scientist with a microscope or other stand-alone equipment, as may have been the case in the past. That same scientist now requires an electron microscope, a range of precision measuring and analysis equipment, computers or supercomputers, databases, and a number of assistants. Advanced disciplines, such as high energy physics, require equipment of such technical complexity and cost that only one or a few units may exist in the world.

Decision makers continue to be confronted with the monumental tasks of determining which facilities and what research activities are to be funded for U.S. basic research. Scientists and administrators increasingly must decide among various promising projects or fields of research because research costs are burgeoning and research budgets are limited. Concern over limited resources for specific objectives extends to the U.S.'s ability to maintain an adequately diverse base of science and technology research activities (National Academy of Sciences 1988). "Base" activities provide the people, knowledge, and infrastructure to carry out science and technology.

4.2.2 Balancing of Science Priorities

Decisions often must be made among vital projects that are competing for the same resources, and these decisions often cannot be based solely on scientific criteria. Political and social considerations may be as important a part of the decision process as scientific merit. For example, much of the debate over the siting of the Superconductor Super Collider (SSC) stemmed from the states' desire to be chosen for receiving a large facility and the associated local economic benefit.

In addition to choice of research topics, "balancing" also affects such issues as few, large centrally directed research projects (such as the SSC) and many, small team or individual research projects of great diversity; near-term and long-term results; public and private sector investment; university and government research support; and international competition and cooperation.

The questions of balance in science priorities have no permanent answers. A healthy science enterprise requires that priorities constantly be debated in the light of new conditions and that the balances be changed in a continuous and orderly manner.

4.2.3 Supply of Scientists and Engineers

Maintaining an adequate supply of technical manpower is critical to the nation's capabilities in basic research. As the world becomes more technologically dependent, greater numbers of scientists, engineers, and technicians are required to identify, characterize, develop, and use new technologies.

Figure 4.1 shows that other major world economic powers (France, West Germany, Japan, and the United Kingdom) are increasing their R&D workforces of scientists and engineers (measured per 10,000 labor force population). The ratio in the United States has remained relatively constant for 20 years, while all of the other countries have virtually doubled their scientific proportion of the total labor force. Japan has nearly tripled its proportion of scientific personnel and now has a scientific/labor force ratio similar to that of the United States (National Science Foundation 1989d).

One concern in the United States is that we will fail to attract enough students in several areas of science and technology that are important to the nation's future. Basic research provides the funding base

Figure 4.1. Scientists and Engineers Engaged in R&D^(a)

(a) Source: National Science Foundation (1989d).

for advanced students at the graduate level in universities. Another concern is that an increasing proportion of science and technology students in U.S. schools are foreigners who return to their own countries, increasing the potential for a shortage of U.S. capabilities in important areas (National Science Foundation 1989c). [The education sector profile, *Education: Investing in Human Resources* (working draft), addresses this subject in more detail.]

4.2.4 Access to Knowledge

The worldwide scientific knowledge base has grown to enormous proportions and continues to expand at an accelerating rate. This "knowledge explosion" poses problems to scientists because it takes time, equipment, and personnel to verify that one's research is not duplicative and to take advantage of the work of other scientists (particularly those in related disciplines). It also poses problems to the science and technology policy maker seeking to balance priorities based on up-to-date information.

Most significantly, at the level of basic research, the work of various disciplines has become increasingly interrelated and interdependent. As a result, ensuring efficient cross-fertilization of ideas and knowledge among research work in the various branches of chemistry, physics, biology, and mathematics is considered an essential part of maintaining a healthy science enterprise.

4.2.5 Cooperation and Coordination in Solving Key Problems of Global Importance

A principal challenge facing society and the science community today is cooperation and coordination to solve large-scale problems that cross both national boundaries and fields of science. The benefits of international collaboration are now generally recognized (Congressional Budget Office 1984):

The increased efforts of other countries should be welcomed as a potential source of advances that can be adopted and exploited by American industry, balancing the traditional postwar flow of scientific knowledge from this to other countries Greater international scientific cooperation could play an important role in increasing the tempo of scientific progress and boosting the growth prospects of the world economy.

Scientific problem-solving at the global level is relatively new, so there is little experience with effective management, particularly when the cooperation and coordination cross national boundaries. A few examples of U.S.-foreign collaboration in physics are summarized in Appendix A.

Cooperation and coordination across science disciplines are needed to address several critical global issues. For example, cutting back chlorofluorocarbon (CFC) production while maintaining the current standard of living cannot occur without major technical efforts to develop alternatives to CFCs in their many uses. Addressing ozone depletion involves meteorologists, atmospheric chemists, refrigerant chemists, cooling equipment engineers, solvent chemists, and manufacturers of foam-blowing equipment, to name just a few.

Other contemporary problems requiring cross-disciplinary cooperation and coordination include the threat of global climate change, depletion of coastal and oceanic biotic resources including fisheries, acid deposition from burning fossil fuels and its impacts on water and forest resources, the worldwide AIDS epidemic, and the need to develop renewable and nonpolluting energy supplies.

4.2.6 Accelerating Transfer of Research Results

Linking investment with anticipated return is becoming more important as policy makers justify decisions to allocate limited resources, particularly in light of the escalating research costs. Basic research is inherently difficult to link with anticipated short-term return because of the uncertainty of the results. It is partly for this reason that private industry does not invest heavily (in relative terms) in basic research. As government agencies are required to indicate anticipated return on investment more closely, basic sciences will be put in an increasingly difficult position. The challenge is to accelerate the process by which the results of basic research are made available for use by applied researchers, thereby strengthening the perceived links among basic science, applied technologies, and subsequent economic return.

4.2.7 Public Understanding and Perception of Science

The general scientific understanding of the U.S. population as a whole has been declining. Recent survey results show that U.S. citizens are far behind their Japanese and European counterparts in basic knowledge of mathematics, chemistry, and physics. The American Association for the Advancement of Science (AAAS) (1989) describes the problem as follows:

The terms and circumstances of human existence can be expected to change radically during the next human lifespan. Science, mathematics, and technology will be at the center of that change—causing it, shaping it, responding to it. Therefore, they will be essential to the education of today's children for tomorrow's world Without a scientifically literate population, the outlook for a better world is not promising.

According to the AAAS, most Americans are not sufficiently literate in science and technology, and a vast revamping of the educational system must be undertaken. To maintain a technologically based society, the United States must improve the general public's fundamental level of technical knowledge and acceptance of science. Part of the progress needed for change involves establishing stronger, more effective lines of communication between the science and education sectors.

4.3 FOCUSING BASIC RESEARCH ON THE NATIONAL ENERGY STRATEGY

The nation's energy future is among the compelling national interests asserting a claim to the nation's scientific resources. The future of energy is embedded principally within those challenges pertaining to the natural resource base. Energy, as currently used by society, is primarily a depletable resource; there are known and limited global reserves of crude oil, natural gas, coal and uranium. Moreover, it is the use of this depletable energy that has contributed to some of the other global problems challenging the science enterprise, such as climate change and human health, and causing the pollution of other natural resources, such as air and water.

The challenge to the science community is to 1) decrease the rate of resource depletion in the short term to reduce environmental impacts and to extend the life of the resource base, and 2) develop totally new, nondepletable and environmentally benign, bulk-energy sources for the long-term future. Scientific knowledge has a critical role to play in these endeavors, by providing knowledge that results in the application of new materials and energy-related conversion and use processes.

The logical starting place is with the top policy leaders in both energy and science. These leaders include Congress, the President's science advisors, the National Science Foundation, and the DOE. The leaders need to address several questions, including:

- For each of the NES goals, what range of basic research needs to be pursued in government agencies, in universities, and between government and the private sector?
- What is DOE's specific role in terms of:
 - national leadership to influence the agenda of the basic research enterprise in the public, academic, and private sectors?
 - its own direct investment in a basic research portfolio?
- How should the various stakeholders with energy or research interests be involved in the process?
- What policy tools are needed to motivate the research community on behalf of the energy goals? (Example tools include federal programs and investments, regulations on patents and intellectual property, incentives, information services, cost-sharing, and international cooperation.)

Answers to these questions are difficult to obtain because policy makers are dealing with moving targets of national need, technological capability, and scientific knowledge. Therefore, the answers need to be tailored to each of the energy and research sectors, and also to a particular period of time. The process needed would allow effective policies relating to basic research for energy to be continuously formulated, evaluated, and adjusted.

In the following chapter, a number of options are presented as contributions to exploring some of these decision problems.

5.0 OPPORTUNITIES TO ENHANCE BASIC SCIENCE CONTRIBUTIONS TO NATIONAL NEEDS

A wide range of exciting opportunities exists for the U.S. science enterprise to address the challenges identified in the previous chapter. Those opportunities apply both to public and private science organizations throughout the country, and strategies for pursuing them will involve the federal government in partnership with the private sector and the university research community. This chapter identifies several key opportunities that support three fundamental goals:

- expand the general science knowledge base to stimulate innovation and discovery in all areas of science and technology, and to address science issues of global significance (Section 5.1)
- upgrade the nation's science enterprise and its basic research infrastructure in order to promote increased excellence and productivity in science (Section 5.2)
- conduct basic research in strategic areas to support development of technology and products needed to carry out the NES (Section 5.3).

These goals correspond to the three areas of science challenges described earlier. The opportunities which follow are examples and are not intended as a complete inventory of possibilities for action. Rather, they represent candidate options for discussion and review, possibly as elements of broader science and technology policy within and beyond the framework of the NES. While these options are presented as discrete actions, it must be understood that effective policies will recognize the interrelationships and address these issues in an integrated manner.

5.1 FUNDAMENTAL RESEARCH OPPORTUNITIES TO ENHANCE THE GENERAL SCIENCE KNOWLEDGE BASE AND STIMULATE INNOVATION

Confronting the science challenges for the twenty-first century requires a broad base of fundamental research at the frontiers of current knowledge. The objective is to stretch our scientific and technological limits, ultimately pointing toward the discovery of innovative concepts, behaviors, and materials. There are many practical results of basic research that did not originally have applications in mind. Such basic research is a generator of opportunities and often motivates entirely new fields of applied R&D having far-reaching economic and social impact. For example, transistors were invented as an outgrowth of research on the quantum theory of solids. Electrical power and communication technologies grew out of original studies on the natural phenomena of lightning in thunderstorms and magnetism in certain minerals. Modern high energy physics research has resulted in major advances in the technology for superconducting magnets and has provided very precise methods to detect radiation of all kinds (Sigma Xi 1989).

No one can predict precisely what discoveries and breakthroughs will result from a continuing investment into basic research. Nevertheless, it is possible to identify the areas of basic knowledge that are likely to stimulate technological innovation and to provide the scientific understanding needed to shape our social and environmental policies:

- *physics* - Because of its relationship to defense and to energy applications, physics is a principal focus of DOE and Department of Defense programs. Priority areas of inquiry include high energy physics to expand understanding of matter, force fields, and energy at the most fundamental particle level; nuclear physics to enlarge our understanding of the interaction, properties, and structures of nuclei and nuclear matter; and fusion energy to establish the knowledge base needed to ultimately capture and control energy from the fusion reaction, the same reaction responsible for the energy of the sun. Work also is needed to enhance the foundation of knowledge for future developments in lasers, superconductivity, fiber optics, and the nature of materials. Basic physics knowledge also has relevance to virtually every other field of scientific research (National Academy of Sciences 1986).
- *chemistry* - Fundamental chemical research provides baseline knowledge critical for the biological and earth sciences, as well as many areas of industrial innovation, including energy conversion processes, new materials development, and materials production. Progress in chemistry is of particular importance in environmental applications such as predicting and controlling air and water pollution and managing toxic and hazardous wastes. Important areas of research include polymers, ceramics, molecular biochemistry, organometallics, atmospheric chemistry, electrochemistry, and geochemistry.
- *biological sciences* - Further work in molecular and cellular biosciences will contribute to advances in biotechnology for human health, food, and energy supply. Basic research is also essential at the systems level to better understand the ecology of the earth at different scales. Categories of important knowledge include biogeochemical dynamics, ecological system processes and dynamics, climate and hydrologic systems, human interactions, and earth systems history. Understanding ecological systems behavior is essential to helping human communities develop new equilibria with natural systems. Current high-impact projects include research on mapping the human genome.
- *mathematical and computer sciences* - Mathematics is the foundation for virtually all science and technology theory, while computers are the tools for applying our knowledge of mathematics to the modelling of scientific phenomena. Computers are also essential to research work for storing, retrieving, and communicating research databases. Finally, computers are essential components of current and developing systems of instrumentation and control in all fields of research, communication, transportation and energy management.
- *atmospheric, oceanic, hydrologic, and earth sciences* - The National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, and the National Oceanic and Atmospheric Administration are the principal supporters of basic research covering various programs to improve our understanding of the behavior of atmospheres, oceans, and terrestrial systems on a global scale. Remote sensing and satellite technologies are among the keys to further knowledge in these fields. These are very diversified areas, which include the properties of soils in relation to agriculture and forestry, and fundamental studies of the geochemistry and geophysics of rock-fluid systems. The basis of science knowledge needs to be enlarged to help improve our ability to continue to live off of the basic resources provided by the earth: water, food, fiber, energy, and mineral wealth. In addition, much of this knowledge will be applied to the problem of long-term disposal of radioactive and other hazardous waste and to a general environmental protection program.
- *electrotechnology, mechanical, chemical and materials engineering* - These traditional areas of applied research provide a foundation for industrial productivity and the U.S. competitive position in

the world. These engineering practices all depend on original basic and applied research in advancing the state of the art. Moreover, they are not totally isolated practices, and any particular application or advance is likely to draw on knowledge across the science and technology spectrum. While government participation is important in these areas, the private sector generally makes the engineering advances that incorporate the results of basic research in these fields into products and processes for the U.S. and global markets. These applied technologies also provide the instrumentation and other technical supports for the work of basic research.

Together, these pursuits form a broad-based U.S. research agenda that can provide a range of unforeseen benefits if they are pursued with adequate support and guidance. While benefits from any single specific activity may be difficult to quantify, the science and policy communities agree that a strong foundation of general scientific and technological research in these and other areas is essential to long-term national well-being.

5.2 OPPORTUNITIES TO UPGRADE THE SCIENCE ENTERPRISE TO ENSURE CONTINUED BASIC RESEARCH EXCELLENCE AND PRODUCTIVITY

As discussed in Chapter 2, the United States currently has the world's strongest program in support of basic science. It has a rich history of technical, economic, and social accomplishments and substantial impacts on the world community. However, as Chapter 4 indicates, that position is shifting. Several other nations, notably Japan, the Soviet Union, and some members of the European Community, have developed strong and competitive basic research--undertakings enabling them to exceed the United States in some areas of science. At the same time, the U.S. science community is experiencing internal weaknesses that could undermine its continuing growth and effectiveness. The future of U.S. global leadership and prestige in many areas of science is at stake.

Opportunities for enhancing the effectiveness of basic research to contribute to the nation's science challenges fall into four general areas:

- *increasing the size and stability of the technical resource base supporting basic research* - The rising costs of research and projected limitations in technical manpower are areas of concern. To address these challenges, science leaders must consider ways to provide the additional funds needed to preserve a "critical mass" of activity, facilities, and qualified scientists in selected areas of national importance. Beyond funding increases, options can include strategies that make existing resources go further; examples include more scientific collaboration, better coordination and sharing of research facilities and equipment, a limit to the number or extent of technical areas pursued, and improvements in research productivity. Multiyear funding of science programs would also be a vast improvement over annual budgeting by reducing inefficient swings in support. Although potentially effective in improving resource use, these options bring the danger of undesirable interference or restrictions to free scientific inquiry. Thus, dealing with basic science resource limitations is a sensitive issue that will require a mixture of increases in support and some forms of resource leveraging for improvements.
- *establishing federal research priorities and planning science investments* - With increasingly limited research budgets and a wide array of promising scientific research opportunities, better efforts are needed to set balanced federal research priorities. This need can be addressed by developing and

using better criteria and methods to evaluate the scientific merit and potential benefits of programs. Improvements can also be made in linking advisory panels more strongly to the implementation of science policies. Finally, use of systematic decision tools can be beneficial in developing and processing decision information.

- *enhancing the relationship of federal science activities to industrial and international basic research* - Although most basic science is conducted without direct focus on its eventual uses, the national basic research enterprise should be managed to continually improve both production and exploitation of new technical knowledge. Two important opportunities for gains are continued revitalization of the nation's industrial research and the strengthening of international science collaboration. This can be done through measures such as joint government-industry-university basic research programs, industrial research consortia, and agreements to develop complementary scientific capabilities. Better means to manage intellectual property rights are needed to deal with conflict of interest problems that pose barriers to collaborative work. Collaborations between industry and universities, such as those sponsored by the National Science Foundation, offer commercially useful results. For example, the collaboration between the nascent German-Swiss pharmacology industry in the early part of the century provided the basis for most of our start-up knowledge of organic chemistry (Pagels 1989).
- *broadening public understanding and appreciation of science to strengthen the nation's technical foundations* - In the United States the current public understanding of science is inadequate to sustain a technological-based society (American Association for the Advancement of Science 1989). Even public attitudes toward scientific solutions for problems and scientific careers for the nation's youth are inadequate to maintain national science leadership in the global community. To help invigorate the nation's science awareness, the federal government can increase its commitment to strengthen precollege scientific and mathematics programs and to promote public involvement in important science decisions, events, and contributions.

Although these activities focus on basic science, pursuing specific opportunities is likely to yield dividends for all other areas of national science and technology enterprise.

5.3 STRATEGIC BASIC RESEARCH GOALS TO SUPPORT THE NATIONAL ENERGY STRATEGY

As mentioned earlier, the elements of the NES are designed around three broad national energy goals:

- ensure adequate supplies of energy at reasonable cost
- maximize efficiency in energy production and use
- improve environmental quality.

Meeting these goals presents serious technical challenges for all phases of the technology development process; successfully overcoming the obstacles requires important new understanding of how energy and environmental systems operate. To fulfill its role in addressing these technical needs, basic research must provide both steady increases in fundamental knowledge of energy and the environment,

and technological breakthroughs that currently cannot be foreseen. Although much of this contribution will come as unanticipated benefits of basic research, many important technical directions for new progress can be indicated.

5.3.1 Ensure Adequate Supplies of Energy at Reasonable Cost

Fossil energy in the form of petroleum, natural gas, and coal currently dominates the energy infrastructure throughout the world and will continue to play a significant role for many years to come. However, supplies of these fuels will become increasingly limited during the twenty-first century, and continued use of current fossil energy technology poses threats to the global environment. Therefore, the nation needs both new sources of these fuels and safe and efficient methods of exploiting their energy content. Moreover, a safe and secure energy future also requires the nation's energy agenda to develop plentiful and clean alternative fuel sources. Basic science must address these needs in the following areas:

- *plentiful and clean fossil fuels* - Important new basic knowledge is needed to discover and exploit new supplies of fossil fuel, to convert them into liquid and gaseous forms for clean use, and to improve their combustion efficiency for various processes in the electric power, industrial, buildings, and transportation sectors. As examples, excellent research opportunities exist in the geosciences, fuel conversion chemistry, biochemical conversion mechanisms, combustion dynamics, and chemical reaction alternatives to combustion.
- *safe and cost-effective alternative fuels* - Two broad sources of nonfossil alternative fuels are attractive in the near term: renewable technologies and nuclear fission. The scientific principles are well established, but basic science must provide a better understanding of their properties and the types of materials or processes needed to capture and convert solar and nuclear radiation. Improvements are needed in cost effectiveness, safety, and environmental protection. For instance, basic research in photon-material interactions and development of advanced materials are important for photovoltaic energy systems. In the very long term, hydrogen fuel, which can be produced using renewable technologies and nuclear fusion, offers sufficient potential value to warrant sustained research investment now. The basic physics of fusion is still not well understood, and the chemical interactions of hydrogen with other materials for safe manufacture, storage, and transport are important research targets.

5.3.2 Maximize Efficiency in Energy Production and Use

Largely because of energy-efficiency gains, the United States used virtually no more energy, and less petroleum, in 1987 than it did in 1973, despite steady growth in the nation's population and GNP (DOE 1989). Much of this improvement was due to applying advanced technology, and many respected studies have concluded that significant additional savings can be achieved cost-effectively (e.g., Carlsmith et al. 1990; Chandler et al. 1988; Goldemberg et al. 1988). In addition, improvements in energy efficiency are vital to resolving several domestic and global energy problems, including the increasing dependence on imported oil, high energy costs, and several environmental problems, particularly harmful atmospheric emissions.

Considerable progress in energy-efficient technologies can be achieved by applying existing basic knowledge through engineering research and technology development or demonstration. However, important new basic knowledge is needed to make fundamental changes in energy use that could dramatically reduce energy intensity. Basic research in generic areas such as combustion, heat transfer,

materials, tribology, and electrochemistry could lead to very important strategic changes in energy-intensive processes and could significantly increase fuel flexibility, efficiency, and handling ease. Three important areas with many long-range research opportunities are mentioned below:

- *basic industrial materials conversion* - Basic research can vastly improve methods for converting basic industrial materials such as metals, paper, textiles, and chemicals--including waste materials. Advances are also needed at the molecular level in physical and chemical knowledge of separation and catalysis processes, thermal processing, and electrochemistry.
- *behavior of new materials and fluids* - Understanding how to develop, apply, and control a number of advanced high and low temperature materials holds promise for improving the conversion or storage efficiencies of many energy-intensive components or systems; examples include engines, furnaces, lighting, windows, and rotating machinery. The features of multiphased and multifluid flows need to be examined for working fluids, waste streams, and advanced heat-pumping or power cycles. Very important fundamental work is still needed to characterize the properties and mechanisms of known and potential superconducting materials and of material degradation and wear.
- *mechanisms of new chemical, electrochemical and biological processes* - Several biotechnology, electrotechnology and chemical conversion processes offer important long-range potential to improve energy use, particularly in industry. Basic work on the mechanisms and energetics of how known and potential processes work is vital to future progress in technology applications.

Progress in social and behavioral research also is needed to better understand the fundamental determinants of energy and advanced technology use in the United States and global economies. Basic research in these and other areas will contribute to the development of entirely new processes and applications, which will yield near-term and long-term payoffs.

5.3.3 Improve Environmental Quality

Environmental concerns have been prevalent in all recent assessments of the nation's future energy needs. Continued damage to many aspects of the environment makes it increasingly critical to understand the environmental impacts of all new energy technologies and energy growth strategies. Just as underestimating these impacts can drastically impact our environment and health, overestimating them can block viable energy options or add needless expense.

Fundamental new information on terrestrial, atmospheric, and ocean ecosystems is essential both to understand the effects of current energy systems and to provide a knowledge base for unanticipated impacts of future systems. Building these knowledge bases can return important unanticipated dividends. For example, basic atmospheric chemistry measurements lead to the discovery of stratospheric ozone depletion and prompted bans on the responsible CFC materials (Rowland and Molina 1975). When acid rain was recognized as a serious environmental problem, basic work begun earlier in 1968 was responsible for providing essential data on the buffering capacity of soils (Johnson and Van Hook 1989).

Several important environmental and health problems have recently taken on increased importance for the basic science community. These problems can be found in areas ranging from the vast reaches of the upper atmosphere to the enclosed environments of many homeowners. Three broad areas of environmental concern from energy system impacts form central thrusts for needed basic research:

- *global climate change* - One general area of concern is the potential effects of greenhouse gas emissions on global climate changes. Analyzing historical climate records and measuring and understanding the direct and feedback roles of clouds, oceans, and soils will add important information to the climate knowledge base. Better global circulation models that include such information and a better understanding of biological systems will add to our understanding of basic climate-shifting forces and trends.
- *hazardous releases and wastes* - Surface environmental and health problems from exposure to long-lived hazardous materials, both radioactive and nonradioactive, are another area of concern. Understanding the interactions among groundwater, soils, rock structures and contaminants is important in making decisions concerning management, cleanup, and disposal of hazardous wastes. Health aspects of these materials also need to be studied.
- *fragile ecosystem impacts* - Integrated long-term research on how sensitive ecosystems such as the Arctic are impacted by natural disasters and by human activities is needed. Measurements of the mechanisms, pathways, extent and duration of ecosystem impacts at basic levels provide essential knowledge to evaluate, protect, and restore these sensitive and vital areas of the environment.

5.4 CONCLUSION

This Profile has presented a picture of basic research that is mixed in important ways. On one hand, it has drawn attention to the long history of scientific accomplishments that are so vital to our current way of life and to the proud heritage of the science enterprise around the world. On the other hand, it has outlined several serious challenges that are facing today's science and policy leaders and that must be addressed to maintain a strong science presence. Moreover, it has pointed out that to meet our long-term energy needs and sustain our nation's technical base, a strong and enduring domestic basic research enterprise is essential.

Fortunately, the Profile also indicates that a vast array of exciting opportunities for U.S. basic research exists. However, results from these opportunities in the form of discoveries and breakthroughs cannot be taken for granted. The resources, priorities, and productivity of the science enterprise need to be enhanced, and the time for decisions and actions is now. If properly nurtured, fundamental research will continue to provide the necessary knowledge and capabilities to maintain the nation's energy, environmental, and economic health well into the twenty-first century.

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APPENDIX A

THE U.S. DEPARTMENT OF ENERGY'S PAST AND CURRENT ROLE IN BASIC SCIENCE

APPENDIX A

THE U.S. DEPARTMENT OF ENERGY'S PAST AND CURRENT ROLE IN BASIC SCIENCE

This appendix provides more detail on the U.S. Department of Energy's (DOE's) historical involvement in basic energy research, the current organization of that research, and the breadth of that research. Specifically, Section A.1 gives a brief history of federal energy research. Section A.2 describes the organization of DOE's Office of Energy Research, which has the primary responsibility for determining and recommending to the Secretary of Energy the overall energy research direction. In Section A.3, DOE-supported research facilities and resources are described, and in Section A.4, representative DOE-supported accomplishments in basic research are described. Section A.5 summarizes new and continuing major initiatives for basic research. Finally, Section A.6 provides a few examples of U.S. and foreign collaboration in physics.

A.1 HISTORY OF FEDERAL ENERGY RESEARCH

Federal support for energy research originated in the Bureau of Mines (BOM) within the Department of Interior. The BOM research effort was initiated in 1910 to perform *applied* research on the fuel quality of various coal types. Four years later, the Bureau established a petroleum division that focused on applied research to improve drilling and recovery techniques.

Federal funding for *basic* research really did not begin until World War II, with the effort to develop an atomic bomb (the Manhattan Project). Under the auspices of the Office of Scientific Research and Development, the federal government assembled a large team of scientists and a network of research facilities devoted to basic research in high-energy and nuclear physics, and biological studies of radiation to protect the health of its employees during R&D activities. A second project was funded, a small energy research effort to develop alternatives to petroleum-based fuels through the Synthetic Liquid Fuels Act of 1944 (BOM and Department of Agriculture) but was once again primarily applied research.

The first Atomic Energy Act was passed in 1946, establishing the Atomic Energy Commission (AEC). The AEC's initial goals for applied research were to further develop nuclear weapons and to develop nuclear energy as a power source for submarine propulsion. The AEC also supported general nuclear power development, but the secret nature of fission research kept these results highly classified. The Act authorized the AEC to conduct R&D related to using fissionable and radioactive material for medical, biological, and health purposes; and to conduct research on the health effects of radiation in order to establish health guidelines.

Later amendments to the Atomic Energy Act in the early 1950s increased private sector involvement in nuclear power development. A plan had been established to develop several reactor prototypes, including the first commercial nuclear power plant at Shippingsport, Pennsylvania, in 1957. However, this was still largely a federal effort, and only with the Atomic Energy Act in 1954 was the private sector given permission to freely explore nuclear power generation.

AEC support for basic energy research during the 1950s emphasized the nuclear sciences. Support included funding for high-energy physics facilities such as the Bevatron at Berkeley, the Cosmotron at Brookhaven, and Synchrotrons at Argonne and Brookhaven National Laboratories. Theoretical studies of controlled thermonuclear reactions were supported at Berkeley, Livermore, and Los Alamos; and approval was given to construct a fusion test device, the stellarator, at Princeton University.

Most federal energy research during from the 1940s through the 1960s can be characterized as long-term basic research in nuclear technology. It was not until the early 1970s that the AEC began to expand its energy research program to include other technologies. Some non-nuclear energy research continued within the BOM, while the National Science Foundation (NSF) began funding solar research in the early 1970s in support of the National Aeronautics and Space Administration (NASA).

The Arab oil embargo and the energy crisis of 1973 gave an impetus to federal energy research outside of the nuclear area. The Energy Research and Development Administration (ERDA) was established in 1974 and assumed the research functions of the AEC while expanding into areas including solar, renewables, and fossil technologies. ERDA was responsible for basic R&D of high-risk technologies; but once these technologies approached commercial feasibility, the burden of development was expected to shift to the private sector. ERDA was established with a strong emphasis towards being a "partner" with private industry in energy R&D.

With the increased recognition of energy as a national priority, all federal energy activities were consolidated into one cabinet-level department, the DOE, on October 1, 1977, by the Department of Energy Organization Act (42 U.S.C. 7101, 7131). The Act, signed August 4, 1977, consolidated all major federal energy activities, including research, regulation, and policy. These activities and organizations included ERDA, the Federal Energy Administration, the Federal Power Commission, regional power administrations such as Bonneville, and energy functions of several other cabinet-level organizations, including the Departments of Interior and Commerce.

Energy research in the 1980s saw a re-emergence of the emphasis towards long-term, high-risk, basic research. Development and demonstration projects have again become the responsibility of the private sector. The character of basic energy research now encompasses all aspects of energy technology from high energy and nuclear physics to global climate change research.

A.2 DOE'S OFFICE OF ENERGY RESEARCH

The Director of the Office of Energy Research (ER) has the primary responsibility for determining the most effective overall energy research direction (for example, the choice between applied and basic research) and for initially making large facilities decisions [such as the Superconducting Super Collider (SSC)], which are then provided to the Secretary in the context of advice and recommendations for Departmental action. The Director also acts as the chief science advisor to the Secretary of Energy. In the following subsections, the organization of DOE's ER is described, along with its oversight and advisory activities and research planning.

A.2.1 Organization of the Office of Energy Research

DOE's Office of ER has sole responsibility for basic research at DOE. Total funding for ER in FY 1989 was approximately \$2.2 billion (See Table 3.6). Basic research supported by ER often crosscuts

disciplines outside of DOE's central energy focus because of broad impacts of energy activities or because of universal research themes. Basic research within ER is organized into five major program areas:

- High Energy and Nuclear Physics
- Superconducting Super Collider
- Fusion Energy
- Basic Energy Sciences
- Health and Environmental Research.

These offices are supported by the Office of Field Operations at DOE Headquarters. Decision-making is centralized within these offices, including development of funding priorities and program planning. Table A.1 lists each office and its FY 1989 appropriations. Each program area is briefly described below.

Office of High Energy and Nuclear Physics

The purpose of the Office of High Energy and Nuclear Physics is to understand the fundamental constituents of matter, energy, and the basic forces of nature. The Office's High Energy Physics Program primarily focuses on the theoretical and experimental investigation of the four known basic forces of nature: electromagnetic, weak nuclear, strong nuclear, and gravitational. This research requires several large experimental facilities including synchrotrons and accelerators. As the state of the art is advanced, increasingly larger facilities are required to remain at the cutting edge of this science. The scientific community's support of the SSC exemplifies the commitment to advances in this field.

The Office's Nuclear Physics Program is focused on investigating atomic nuclei and nuclear matter. This program is divided among medium and lower energy nuclear physics, heavy ion nuclear physics, and nuclear theory. Once again this research relies on access to several large facilities, mostly accelerators, and also on the calculating abilities of state-of-the-art supercomputers. The general research community has access to these facilities based on the merit of the proposed work.

Office of the Superconducting Super Collider

The Office of the Superconducting Super Collider was established on January 13, 1989, and helps support the Director of ER in planning, developing, and implementing the SSC program. This program includes R&D; construction management systems; compliance with environmental, safety, and health regulations; international collaboration; liaison with state and local governments, universities, industry, the public, media, and Congress; and the design, construction, operation, and maintenance of the accelerator.

Office of Fusion Energy

The goal of the Office of Fusion Energy is to establish the basic science and engineering required for developing fusion power. This goal is being pursued through research into properties of plasmas

Table A.1. Office of Energy Research, FY 1989 Appropriations^(a) (\$ millions)

High Energy and Nuclear Physics	823.5
High Energy Physics	559.4
Nuclear Physics	260.9
General Science Program Direction	3.2
Superconducting Super Collider	98.6
Operating	82.6
Capital Equipment	16.0
Fusion Energy	350.7
Applied Plasma Physics	78.2
Confinement Systems	174.8
Development and Technology	54.1
Planning and Projects	5.0
Program Direction	4.6
Capital Equipment and Construction	34.0
Basic Energy Sciences	549.3
Material Sciences	180.5
Chemical Sciences	132.9
Engineering and Geosciences	33.2
Applied Mathematical Sciences ^(b)	42.7
Advanced Energy Projects	14.5
Energy Biosciences	20.6
Program Direction	4.9
Capital Equipment and Construction	120.0
Health and Environmental Research	257.5
Analytical Technology	14.8
Environmental Research	36.6
Health Effects	69.3
General Life Sciences	46.1
Medical Applications	36.6
Carbon Dioxide	17.6
Program Direction	4.0
Capital Equipment and Construction	32.5
Oversight and Advisory Activities	86.2
Energy Research Analyses	3.8
University Research Support	21.7
University Research Instrumentation	5.0
Multiprogram Energy Laboratories	55.7
Applied Mathematical Sciences ^(a)	-
Total	2,165.8

(a) Source: DOE's Office of Energy Research.

(b) Applied Mathematical Sciences is managed by the Scientific Computing staff but budgeted under the Basic Energy Sciences Program.

(Applied Plasma Physics Program), plasma confinement systems (Confinement Systems Program), and materials for fusion systems (Development and Technology Program). Advancements in all of these areas are needed to successfully develop fusion as an energy source. This program strongly emphasizes international cooperation, given both the expense and universal benefits of fusion research.

Office of Basic Energy Sciences

The Office of Basic Energy Sciences (BES) supports long-range basic energy-related research and provides the fundamental scientific foundation for the nation's future energy options. BES is organized along disciplines in material sciences, chemical sciences, engineering and geosciences, applied mathematical sciences, advanced energy projects, and energy biosciences. In addition to supporting research at the national laboratories and universities in these areas, BES directly supports university research through contracts and grants with individual scientists and graduate students. In this way BES helps support the energy knowledge base and ensure the supply of future scientific personnel.

Office of Health and Environmental Research

The mission of the Office of Health and Environmental Research (OHER) is to develop knowledge needed to identify, understand, and anticipate the long-term health and environmental consequences of energy use and development and to use DOE's capabilities to solve major scientific problems in medicine and biology. Health effects research is supported through epidemiological studies on selected human populations exposed to radiation and other energy-related toxicants, and experimental studies using molecular, cellular, and animal test systems. Life science research in structural biology, human genome, and cell repair processes is conducted to provide a fundamental understanding of the cellular and molecular nature of key biological processes.

Analytical technology research develops new measurement concepts, methods, and instrumentation to detect, characterize, and quantify radiation and chemical emissions and exposures. Medical application of nuclear technology has led to the development of new radioisotope-labeled compounds, radiation beams, clinical procedures, and devices for the study, diagnosis, and treatment of human diseases. The ecological research program is concerned with the behavior of energy- and weapons-related contaminants as they are processed through the oceans and terrestrial ecosystem. The atmospheric and climate research program focuses on establishing the quantitative links between use of greenhouse gases (e.g., CO₂) and global climate change.

A.2.2 Oversight and Advisory Activities of the Office of Energy Research

In addition to basic research activities conducted by each ER program office, ER also has staff who support the advisory and oversight responsibilities of the Director of ER. Staff provide independent assessments of research programs (Office of Program Analysis), oversight of research facilities and manpower (Office of Field Operations Management), and ad hoc analyses of issues that impact ER (Science and Technology Affairs staff). Finally, Scientific Computing staff provides support and research in mathematics and computer sciences for many ER basic research programs.

A.2.3 Planning Research within the Office of Energy Research

Each ER office has broad authority to plan and conduct research. While the Secretary determines the overall energy research direction and makes decisions on large facilities, according to national energy needs, the individual offices primarily determine the emphasis within each of the ER areas.

This decentralized planning process allows energy research managers to be more flexible in responding to changing needs and discoveries in the energy area, or in maintaining priorities when resources are limited.

Within the Office, the Director of ER has final approval of any major changes and new initiatives for basic energy research for recommendation to the Secretary. The Office of Program Analysis within the Director's office evaluates the impact of individual energy research programs. Also, ER relies on independent assessments of research programs from such organizations as the National Academy of Sciences and the Energy Research Advisory Board.

A.3 DOE-SUPPORTED RESEARCH FACILITIES AND RESOURCES

In the following subsections, DOE's research facilities and funding of R&D at universities are briefly described.

A.3.1 DOE Laboratories

The DOE-owned laboratories include nine large multiprogram labs, nine major single-program labs, and many other smaller laboratories. Table A.2 lists DOE's multiprogram laboratories, and Table A.3 lists DOE's major single-program laboratories, both as of FY 1989. Although DOE owns the facilities, contractors from universities and the private sector operate most of the laboratories. This government-owned, contractor-operated (GOCO) relationship, a legacy of the successful Manhattan Project, allows talented researchers from universities and private industry to contribute to the nation's energy research needs.

Most of these laboratories house user facilities (Table A.4), which sometimes have unique capabilities. Topics at these facilities range from fundamental science to applied and engineering-oriented research of energy technologies. These facilities are available to all qualified U.S. researchers based on the merit of the proposed research.

Another characteristic of the DOE laboratories is that they foster interdisciplinary research. By building research teams from various disciplines to address a research need, the laboratories expedite the transfer of results across disciplines. The laboratories are to some extent unique in this respect, which is attributable to both management style and the diversity of research conducted under one roof.

A.3.2 University Research

Currently, DOE provides about \$400 million in direct support of university research through project research grants and contracts (see Table A.5). The Office of ER provides nearly 90% of this total (\$354.4 million) and indirectly funds a similar amount through DOE national laboratories and contractor research facilities.

The DOE sponsors research in a very wide range of scientific and technical disciplines. In the fundamental sciences, DOE is the principal supporter of the nation's research in high energy and nuclear physics. Basic energy-related research includes programs in the materials, chemical, and nuclear sciences; engineering, applied mathematics, and computational sciences; the geological sciences; and health, biological and environmental research related to energy sources and processes.

Table A.2. Multiprogram Laboratories, FY 1989^(a)

Laboratory	Operator	Location	Staff	Operating Budget (millions \$)
Argonne National Laboratory	University of Chicago	Argonne, Illinois	3,905	297
Brookhaven National Laboratory	Associated Universities, Inc.	Upton, New York	3,351	241
Idaho National Engineering Laboratory	EG&G Idaho, Inc.	Idaho Falls, Idaho	6,006	503
Lawrence Berkeley Laboratory	University of California, Berkeley	Berkeley, California	2,508	180
Lawrence Livermore National Laboratory	University of California	Livermore, California	8,335	960
Los Alamos National Laboratory	University of California	Los Alamos, New Mexico	7,800	952
Oak Ridge National Laboratory	Martin Marietta Energy Systems, Inc.	Oak Ridge, Tennessee	4,484	425
Pacific Northwest Laboratory	Battelle Memorial Institute	Richland, Washington	2,480	218
Sandia National Laboratories	AT&T Technologies, Inc.	Albuquerque, New Mexico; Livermore, California; and Tonopah, Nevada	8,345	1,060

(a) Source: DOE (1990).

A.4 REPRESENTATIVE DOE-SUPPORTED BASIC RESEARCH ACCOMPLISHMENTS

Many examples demonstrate that the results of basic energy research have directly led to scientific breakthroughs or technological advancements. Results of basic research have broad applications, and knowledge gained in one field often can be applied in other fields. Technologies developed during the research effort also find secondary applications, sometimes proving to be of greater value than the original. Some examples of such applications are briefly summarized.

Table A.3. Major Single-Program Laboratories, FY 1989^(a)

Laboratory	Operator	Location	Staff	Operating
				Budget (millions \$)
Ames Laboratory	Iowa State University	Ames, Iowa	385	22
Continuous Electron Beam Accelerator Facility	Southeastern Universities Research Association	Newport News, Virginia	283	44
Energy Technology Engineering Center	Rockwell International Corp.	Canoga Park, California	160	26
Fermi National Accelerator Laboratory	Universities Research Association, Inc.	Batavia, Illinois	2,140	150
Morgantown Energy Technology Center	U.S. Department of Energy	Morgantown, West Virginia	278	226
Oak Ridge Associated Universities	Oak Ridge Associated Universities	Oak Ridge, Tennessee	525	40
Pittsburgh Energy Technology Center	U.S. Department of Energy	Pittsburgh, Pennsylvania	300	150
Princeton Plasma Physics Laboratory	Princeton University	Princeton, New Jersey	1,060	97
Savannah River Laboratory	Westinghouse Savannah River Company	Aiken, South Carolina	1,250	200
Solar Energy Research Institute	Midwest Research Institute	Golden, Colorado	487	57
Stanford Linear Accelerator Center	Stanford University	Stanford, California	1,520	110
Westinghouse Hanford Company	Westinghouse Electric Company	Richland, Washington	8,700	800

(a) Source: DOE (1990).

Table A.4. DOE User Research Facilities^(a,b)

Ames Laboratory Coal Preparation and Characterization Facility X-Ray Diffusion Laboratory	Oak Ridge National Laboratory Oak Ridge National Environmental Research Park Surface Modification and Characterization Facility Neutron Scattering Facility National Center for Small-Angle Scattering Research Health Physics Research Reactor Holifield Heavy Ion Research Facility Oak Ridge Electron Linear Accelerator Shared Research Equipment (SHaRE) Microanalysis Facility Roof Research Center High Temperature Materials Laboratory Low Temperature Neutron Irradiation Facility Bioprocessing Research Facility Atomic Physics Tandem Accelerator
Argonne National Laboratory 4-MV Dynamitron Facility Argonne Tandem/Linac Accelerator Facility Facility for High-Resolution Atomic Spectroscopy Intense Pulsed Neutron Source I (IPNS-I) Users Support Center Biological-Materials Growth Facility High Voltage Electron Microscope Tandem Facility Janus Biomedical Research Neutron Reactor	Pacific Northwest Laboratory Hanford National Environmental Research Park
Brookhaven National Laboratory National Synchrotron Light Source Alternating Gradient Synchrotron Scanning Transmission Electron Microscopy Facility PETT VI Positron Emission Transaxial Tomography JSW 168 Small Cyclotron 60-Inch Cyclotron Double MP Tandem Accelerator Facility High Flux Beam Reactor	Sandia National Laboratories Combustion Research Facility (Livermore, California) Solar Thermal Test Center (Albuquerque, New Mexico)
Continuous Electron Beam Accelerator	Savannah River Ecology Laboratory National Environmental Research Park
Fermi National Accelerator Laboratory Entire Laboratory	Stanford Linear Accelerator Center Positron-Electron Project Storage Ring Hybrid Bubble Chamber Facility Spectrometer Facility SPEAR Storage Ring
Hanford Westinghouse Laboratory Fast Flux Test Facility	Stanford Synchrotron Radiation Laboratory Entire Laboratory
Idaho National Engineering Laboratory INEL Environmental Research Park	Energy Technology Engineering Center Sodium Pump Test Facility Sodium Components Test Installation
Lawrence Berkeley Laboratory The National Center for Electron Microscopy Bevalac/SuperHILAC Neutron Beam Engineering Test Facility National Tritium Labeling Facility 88-Inch Cyclotron	Geothermal Test Facility Entire Facility
Lawrence Livermore National Laboratory National Magnetic Fusion Energy Computer Center National Gene Library Project	Bates Linear Accelerator Facility Entire Facility
Los Alamos National Laboratory National Flow Cytometry and Sorting Research Resource National Stable Isotopes Research Weapons Neutron Research Facility Clinton P. Anderson Meson Physics Facility National Genetic Sequence Data Bank (Gen Bank) Los Alamos National Environmental Research Park	Grand Junction Facility Uranium Exploration Equipment Calibration Facilities

(a) Source: DOE (1990).

(b) Operating budgets include basic and other research activity onsite or contracted offsite, as well as facility operations and maintenance and other administrative functions. The proportion varies among the laboratories.

Table A.5. DOE University R&D Funding by Research Program (millions)^(a,b)

<u>Program</u>	<u>FY 1988 Actual</u>	<u>FY 1989 Active</u>	<u>FY 1990 Estimate</u>	<u>FY 1991 Estimate</u>
Office of Energy Research				
High Energy Physics	75.4	81.5	89.8	95.2
Nuclear Physics	40.4	42.8	40.5	45.8
Magnetic Fusion	44.6	56.7	52.8	54.1
Biological & Environmental Research	79.1	66.3	69.7	48.8
Basic Energy Sciences	199.0	162.3	127.9	120.1
University Research Support	3.2	9.1	3.0	5.5
University Research Instrumentation	4.8	4.8	4.8	4.8
Subtotal	446.5	423.2	388.5	374.3
Office of Fossil Energy	35.9	33.0	23.3	14.2
Office of Conservation and Renewable Energy	30.2	28.5	22.1	27.7
Office of Environmental Remediation and Waste Management	0.0	0.0	15.7	22.7
Office of Defense Programs	17.0	19.4	16.4	15.0
Office of Nuclear Energy	4.1	3.0	3.2	0.0
Total	533.7	507.1	469.2	453.9
Congress Mandated ^(c)	-135	-92	-20	NA ^(d)
DOE Based on Annual Budget Request	399	415	449	454

(a) Source: Obtained from a DOE Comptroller crosscut table on university R&D FY91 (January 1990 internal document).

(b) Operating budgets include basic and other research activity onsite or contracted offsite, as well as facility operations and maintenance and other administrative functions. The proportion varies among the laboratories.

(c) Congress has voted a variable amount each year to fund specific facilities and projects for DOE's administration beyond DOE's annual budget request. These additional funds are then included in the summary of "actual" program expenditures. Since 1988, DOE and its Office of ER have submitted incrementally increasing budget requests for university R&D. This pattern of increase is shown on the bottom line, most of which was managed by the Office of ER.

(d) Not available.

A.4.1 Molecular Beam Application

Nobel Laureate Y. T. Lee at the University of California has obtained surprising results using molecular beams to study chemical reactions of energetic benzene molecules. Using laser radiation, Professor Lee is able to cause individual benzene molecules to begin to degrade chemically, just as they would do in the environment characteristic of combustion. His experiments have demonstrated surprisingly extensive rearrangements of benzene's constituent hydrogen and carbon atoms - much more extensive than would have been anticipated from conventional chemical wisdom. This research has potentially far-reaching implications for chemistry and, ultimately, for the design and control of optimum combustion systems.^(a)

A.4.2 Synthesis of Silicon Carbide

Ames Laboratory has developed a new, simple, and efficient way to synthesize silicon carbide. This new approach, which makes it possible to produce silicon carbide in the form of fibers, is likely to cut both the time and the cost of current commercial production of silicon carbide fibers. Materials containing these silicon carbide fibers are replacing metal in industrial and military applications because of their strength, low weight, high heat tolerance, and resistance to chemical breakdown. A patent application has been filed, and several industrial concerns have expressed serious interest in this new development.^(a)

A.4.3 X-Ray Laser Microscope

Scientists at the Princeton Plasma Physics Laboratory have developed an x-ray laser microscope that is capable of revealing the details of biological systems. This accomplishment, which was recognized by a 1989 R&D 100 Award, allows scientists to take pictures of living cells and observe such processes as the invasion of a virus. The availability of this microscope is expected to greatly expand our ability to study the structure and dynamic processes of biological cells.^(a)

A.4.4 Advance in Imaging of Material Defects

A new imaging technique at Oak Ridge National Laboratory can "see" new details of defects in high-temperature superconductors and many other materials. Using this technique, scientists have learned that achieving high critical current densities in the oxide superconductors depends strongly on the geometry of certain defects. These high current densities are one requirement for practical applications of high-temperature superconductors in electric motors, generators, and transmission lines. This result leads to renewed optimism that current densities in high-temperature superconductors can be raised to useful levels.^(a)

A.4.5 Thermally Unstable Complexants

At Argonne National Laboratory a new class of chemicals has been developed for environmental and nuclear waste applications. These chemicals, called thermally unstable complexants, are environmentally compatible chemical clean-up agents. They remove transuranic and other metal contaminants

(a) Decker, J. F., Acting Director Office of Energy Research, Statement Before the Subcommittee on Energy Research and Development of the House Science and Technology Committee, March 20, 1990, Department of Energy, Washington, D.C.

from waste streams to very low levels and, after further development, could be applied to nuclear wastes, groundwater, and metallurgical processes.^(a)

A.4.6 Mathematics of Concrete Propagating

A mathematical technique makes possible computer modeling of the propagation of cracks in materials, such as airplane fuselages and engine fan blades. The annual cost of fracture-related damage in the United States has been estimated at over \$10 billion. This new mathematical technique, discovered at Oak Ridge National Laboratory, has been implemented in a structural analysis computer program by Cornell University to form a useful tool in material structure studies.^(a)

A.4.7 Chemical Separation and Blood Serum

The DOE supports many efforts involving separation of material constituents by chemical methods. The purpose of basic research in chemical separations is to identify fundamental mechanisms to improve the efficiency or selectivity of separations. The development of artificially synthesized molecules known as ionophores led to a Nobel Prize in Chemistry for Energy Research Grantee Professor Donald Cram of UCLA. Ionophores are crown ether complexing agents that can be used to very selectively extract metallic ions out of solution (DOE 1990).

In a second application, the ionophores were adapted and applied to clinical analyses to detect the presence of potassium and sodium in blood serum. The new method is easier and less costly than traditional separation/isolation methods (DOE 1990).

A.4.8 Explanation for Ozone Depletion

The DOE is developing atmospheric models related to its goal of assessing pathways of energy-related physical and chemical agents in the environment and their impacts on human life. In conjunction with DOE-funded modeling studies at the National Center for Atmospheric Research, the University of California (Irvine) recently developed a theory concerning the suspected reduction of stratospheric ozone by the emission of manmade chemicals (DOE 1990).

The startling depletion of ozone concentration observed in the Antarctic (the formation of an "ozone hole") was probably the first widely accepted evidence that the predicted loss of ozone by chlorofluorocarbon emissions into the atmosphere could be demonstrated experimentally. However, the Antarctic loss phenomenon could not be readily explained until Irvine researchers hypothesized that the ozone depletion was caused by a previously unknown rapid reaction between gaseous chlorine nitrate and hydrogen chloride, ordinarily a gas, on the surface of the cold polar water ice clouds. Recent laboratory results at simulated Antarctic conditions, obtained with NASA funding at NASA's Jet Propulsion Laboratory and the Stanford Research Institute, have validated the chlorine nitrate hypothesis (DOE 1990).

(a) Decker, J. F., Acting Director Office of Energy Research, Statement Before the Subcommittee on Energy Research and Development of the House Science and Technology Committee, March 20, 1990, Department of Energy, Washington, D.C.

A.4.9 New Insights in Subsurface Microbiology

DOE's efforts to investigate environmental pathways of energy-related agents have significantly advanced the world's geological database. DOE has pioneered research in determining the presence, abundance, and diversity of microbial communities in sediments and aquifers up to 2000 feet deep. Scientific results to date are described in a special volume of *Geomicrobiology* (1989). The results of this research have changed current thinking on microbial distribution and the effects of microbial communities on chemical contaminant stability and mobility at low depths. The research has potential long-term benefits to remediate groundwater contamination in zones where no practical cleanup technology exists (DOE 1990).

A.4.10 Improvements in Nuclear Medicine

The Atomic Energy Commission's early work in producing and distributing radioisotopes, along with later developments in radiation detection instrumentation and modern computers, has been a major factor in developing nuclear medicine as a clinical specialty. Recent emphasis has been on improving the spatial and temporal resolution ability of positron emission tomography imaging devices. Attention also is on the more widely available single photon emission computed tomography. The radiopharmaceutical industry relies heavily on the national laboratories as sources of stable and radioactive nuclides. Those laboratories originated many of industry's production methods. Also, as an example of interlaboratory technology transfer, DOE laboratories developed technologies for instrumentation, computers, and nuclear chemistry, which are used in biomedical applications at other DOE laboratories (DOE 1990).

A.4.11 Monitoring of Water Quality and Oceanographic Productivity

Brookhaven National Laboratory (BNL) developed a series of moored instruments for monitoring water quality in many regions subjected to chemical stress. These instruments include a moored fluorometer, a moored oxygen sensor, a monitor for total suspended solids, and a monitor for primary productivity. These instruments also are being used in the Bering Sea, the Mid-Atlantic and South Atlantic Bights, and other regions to understand the variability of physical, chemical, and biological processes affecting the distribution and productivity of aquatic life in coastal areas. In particular, the Suffolk County Health Department (NY) has recently used a BNL-moored fluorometer to monitor water quality in Peconic Bay in real-time by mooring-to-shore telemetry (DOE 1990).

A.4.12 Development of Supercomputers

Computers have become a standard tool in the office and the laboratory to control apparatus and to gather and analyze data. Supercomputers increasingly are being used as numerical laboratories to simulate and study experiments that cannot be practically performed. DOE has been a leader in developing supercomputers for 45 years and has the largest scientific computing center in the world at Los Alamos National Laboratory (LANL), which has the equivalent of 60 supercomputers (DOE 1990).

A current example of societal benefits arising from ongoing basic research at LANL is the multi-cross-bar network that is being developed to help communication among supercomputers. DOE is working with the American National Standards Institute to establish public standards for high-speed computing equipment, which will enable computer users to purchase over-the-counter equipment to link with a national supercomputer network. Such a network will open the vast capabilities of supercomputers to a much larger fraction of the scientific community and will greatly improve information transfer among research facilities (DOE 1990).

A.4.13 Near-Term Benefits of Fusion Science and Technology

Meeting the technological requirements of fusion has led to advances in fields ranging from microwave technology, to materials science, to applied superconductivity. In addition, plasma physics, the major academic discipline of fusion, has developed into a sophisticated and useful branch of applied science over the last twenty-five years. Besides fusion, plasma physics has also been applied to understanding the earth's magnetosphere, interstellar space, and astrophysical plasmas; and advancing various high technologies, such as x-ray and ultraviolet light sources, free electron lasers, intense charged particle beams, and gyrotrons. Plasma processing, which is used in semiconductor manufacturing, machine tool hardening, and other industrial areas, is also a promising application of plasma physics (DOE 1990).

A.5 NEW AND CONTINUING MAJOR DOE INITIATIVES FOR BASIC ENERGY RESEARCH

The Office of Energy Research (ER) is initiating new programs, which are in response to policy challenges described in Section 4.0. The list of programs is indicative of the response mechanism but is not exhaustive. The Office of ER continues to evaluate, prioritize, and initiate programs in support of the DOE's overall long-term mission. Several new and continuing initiatives are briefly described below.

A.5.1 Human Genome

The purpose of the DOE initiative on the human genome is to develop technologies and provide resources that will allow the human genome to be characterized at the molecular level. This program has three overall objectives: 1) to develop a library of ordered human DNA fragments, 2) to increase the efficiency and thereby reduce the cost of sequencing the genome, and 3) to develop the computer capabilities needed to organize and interpret this data. DOE is in partnership with the National Institute of Health and the National Science Foundation, as well as foreign countries and organizations in this global effort.

The benefits to the DOE from this effort are improved understanding of genetic damage resulting from exposure to radiation and energy-related chemicals. However, the potential benefits of this mapping and sequencing effort extend well beyond these applications. Knowledge of genome maps and DNA sequences may hold the key to identifying the causes and potential treatments of diseases and genetic disorders.

A.5.2 Nuclear and Hazardous Waste

One of DOE's most challenging problems is the minimization, cleanup, and management of waste materials generated from DOE operations. One of the greatest threats posed by DOE and other non-DOE waste sites is to groundwater. Groundwater is the source of drinking water for one-half of the U.S. population.

DOE's Subsurface Science Program, managed by ER's Office of Health and Environment Research, initiated a program to develop a fundamental understanding of the subsurface environment. The subsurface environment is a natural dynamic system where the integrated effects of chemistry,

microbiology, and hydrology control contaminant movement. Understanding the subsurface environment is critical to developing improved predictive tools and cost-effective strategies to avoid, control, and mitigate waste contamination.

A.5.3 Superconducting Super Collider

The President has stated that the SSC is a critical part of the Administration's initiative to strengthen the nation's position as a world leader in science and technology. Maintaining and enhancing the U.S. position in science, education, and technology are critical to future competitiveness in world markets. New knowledge of the fundamental nature of matter and energy and the development of spinoff technologies will produce benefits well into the next century.

The SSC, with a 40-TeV center-of-mass energy, will have more than 2,000% of the energy of any existing collider. The total estimated cost of the SSC is \$5.9 billion; the federal contribution is expected to be approximately \$4.1 billion. With projected construction completion in mid-FY 1998, the SSC, with over 400 staff in 1989, will ultimately have a staff of 2,500 in addition to about 500 visiting scientists.

A.5.4 Global Warming

In response to an international drive to improve the understanding of potential climate change and in collaboration with existing programs at other agencies, DOE has established a focussed program to develop general circulation models that can regionally predict climate effects by the end of the century. A specific initiative intended to substantially improve the quality of radiative transfer models is the Atmospheric Radiation Measurement program, an effort to improve the treatment of radiative transfer under clear sky, general overcast, and broken cloud conditions. This knowledge will help increase understanding of the causes and potential effects of climate change. In turn, policy makers will need this information to gauge the effectiveness of policies designed to mitigate or adapt to climate change.

A.5.5 Advanced Light Sources

Light is an important analytical tool. In essence, the brighter the light (that is, the more intense, the narrower the spectrum, and the easier to focus the light source), the greater the detail that can be revealed and the faster that data may be collected. Light is a nondestructive tool that can be used to examine in detail the structure of materials and nature of surfaces. Understanding the properties of solid surfaces and interfaces among materials in turn will lead to advances in such areas as semiconductors, chemical synthesis, and the study of biological processes.

DOE is developing two new light sources: the 7 GeV Advanced Photon Source (APS) at Argonne National Laboratory and the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory. The light sources are unique in that the APS will operate in the hard (intense, short wavelength) x-ray range of the spectrum, while the ALS will provide light in the ultraviolet and soft x-ray wavelengths. The facilities will produce light of a brightness well in excess of facilities now in operation and will allow scientists to conduct new experiments to examine the atomic structure of matter.

A.6 EXAMPLES OF UNITED STATES AND FOREIGN COLLABORATION IN PHYSICS

The DOE participates in several international collaborative efforts, both bilateral and multilateral. The following are some examples of U.S.-foreign collaboration in physics:

- A \$50 million, 4,500-ton D-0 Detector is under construction at the U.S. Fermi National Accelerator Laboratory (Fermilab). This will be a user facility for basic research in high-energy physics, where 160 physicists from 16 U.S. universities, 3 national laboratories, France, and the USSR will collaborate. The D-0 will double the amount of physics data obtainable at Fermilab.
- Negotiations are under way to incorporate international funding for constructing the SSC and the initial complement of detectors. This facility will benefit from collaborative efforts by the international particle physics community.
- The CERN high-energy physics facilities in Geneva, Switzerland, involve joint funding by 13 European member countries. The United States is not a member state, but U.S. research groups funded by the DOE and by the National Science Foundation have long had access to the CERN facilities. At LEP, the newest CERN accelerator, U.S. groups are involved in developing all four detectors and play a major role in developing one detector.
- The National Science Foundation is funding the institute for Theoretical Physics in Santa Barbara, California, which may have half of its staff in residence supplied from abroad.
- The Stanford Linear Accelerator Facility has strong international participation by researchers, including periods where more than 200 foreign researchers participated in activities for periods longer than 3 months (National Academy of Sciences 1986).
- At the Deutsches Elektronen-Synchrotron high energy accelerator laboratory and HERA electron-proton collider facilities in West Germany, U.S. groups have a significant role in fabricating and using two detectors.
- The Radiation Effects Research Foundation, located in Japan, is a bi-national program between the United States and Japan, and has been supported since 1948. Investigations on the health effects of atomic bomb survivors and their offspring provide the database for estimating human risk to radiation exposure and radiation standards.

A.7 REFERENCES

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APPENDIX B

WORKSHOP ON THE BASIC SCIENCE PROFILE

APPENDIX B

WORKSHOP ON THE BASIC SCIENCE PROFILE DECEMBER 13, 1989 WASHINGTON, D.C.

PARTICIPANTS

Session 1 - Session and Policy Drivers of Science

Michael Crisp	Department of Energy
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Session 2 - Challenges to Excellence

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Session 3 - Leveraging DOE Support of Science

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Seymour Baron	Brookhaven National Laboratory
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Session 4 - Basic Science and the National Energy Strategy

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APPENDIX C

NATIONAL LABORATORY ADVISORY COMMITTEE

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NATIONAL LABORATORY ADVISORY COMMITTEE

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