Chapter 6

Fusion as a Research Program

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Fusion as a Research Program

The ultimate objective of fusion research is to produce a commercially viable energy source. Yet, because the research program is exploring new realms of science and technology, it also provides a weal h of near-term, non-energy benefits. A complete analysis of the fusion energy program must include the immediate, indirect benefits and costs of the ongoing research effort, in addition to its progress in reaching its long-term goal.

NEAR-TERM BENEFITS

Fusion research has provided four major near-term, non-energy benefits. It has been a driving force behind the development of plasma physics. It educates plasma physicists who contribute to fusion and other fields. It produces technologies with valuable applications elsewhere, and it has put the United States in a strong position in the world scientific community.

Development of Plasma Physics

The development of the field of plasma physics was driven by the needs of scientists working on controlled thermonuclear fusion and space science and exploration. In the case of fusion energy,

> The simultaneous achievement of high temperatures, densities, and confinement times [needed for a plasma to generate fusion power] required significant improvements in forming and understanding plasmas confined by magnetic fields or by inertial techniques.[1]

Thus, research conducted on the prospects of fusion energy necessitated concurrent advances in the area of plasma physics, and, in fact:

> The international effort to achieve controlled thermonuclear fusion has been the primary stimulus to the development of laboratory plasma physics.[2]

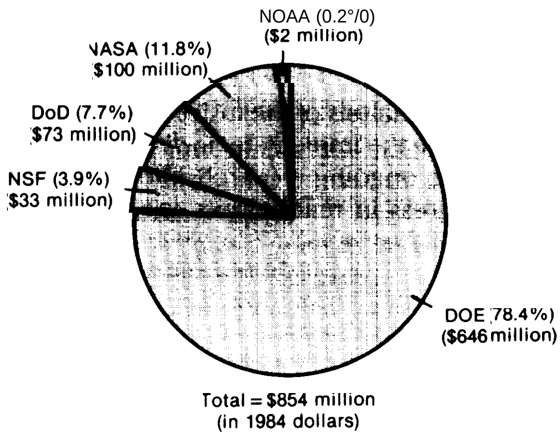
The field of plasma physics has synthesized many areas of physics previously considered distinct disciplines: mechanics, electromagnetism, thermodynamics, kinetic theory, atomic physics, and fluid dynamics. Today, plasma physics goes beyond fusion research. Since most known matter in the universe is in the plasma state, plasma physics is central to our understanding of nature and to the fields of space science and astrophysics. Theories and techniques developed in plasma physics are providing fundamental new insights into classical physics and are opening up new areas of research.

The field of plasma physics has grown rapidly since the 1950s. When the American Physical Society formed the Division of Plasma Physics in 1958, for example, the division had less than 200 members. Today, the Division of Plasma Physics is one of the society's biggest groups, with almost 3,400 members. The careers of most of these members originated in magnetic fusion-related work. In addition, over 40 American universities now have major graduate programs in plasma physics and/or fusion technology. Graduate level plasma physics courses are also taught in applied mathematics and in electrical, nuclear, aeronautical, mechanical, and chemical engineering departments.

As shown in figure 6-1, the Department of Energy (DOE) has played a major role in plasma physics research, funding over three-quarters of federally sponsored plasma physics research in fiscal year (FY) 1984. Virtually all DOE support was directed at fusion applications; 72 percent of DOE's funding was dedicated to the magnetic fusion program, 26 percent funded the inertial confinement fusion program, and only 2 percent ($3 million, in 1984 dollars) was directed at general plasma physics. Outside of the fusion applications, Federal funding for plasma physics

[1] National Research Council, Physics *Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), p. 5.
[2] Ibid.

Figure 6-1.— Federal Funding of Plasma Physics in 1984



NOAA = National Oceanic and Atmospheric Administration
NASA = National Aeronautics and Space Administration
DoD = Department of Defense
NSF = National Science Foundation
DOE = Department of Energy

SOURCE: Adapted from the National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986).

research is very limited. A National Research Council report concluded that "support for basic plasma physics research has practically vanished in the United States, " with only the National Science Foundation providing funds "clearly for this purpose."[3]

Educating Plasma Physicists

Educating plasma physicists, as well as other scientists and engineers, is one of the most widely acknowledged benefits of the fusion program. **Over the last decade, DOE's magnetic fusion program has supported the education of almost all of the plasma physicists trained in the United States.**[4] This achievement is due largely to DOE's commitment to maintaining university fusion programs during a period when budget reductions have forced other agencies to curtail their funding of plasma physics research. In addition, DOE provides 37 fusion fellowships annually to qualified doctoral students.

[3] Ibid., p. 97.

[4] John F. Clarke, Director, DOE Office of Fusion Energy, *Plasma Physics Within DOE and the Academy Report-Physics Through the 1990s,* Department of Energy, Office of Fusion Energy, July 1986, p. 5.

Although DOE supports the education of most of the Nation's plasma physics graduates, the department does not have the resources to employ many of these people. A large fraction of the Nation's plasma physicists are engaged in defense-related work;[5] plasma physicists also work in universities, private industry, and the National Aeronautics and Space Administration (NASA) space science program. Education in plasma physics and fusion research enables these scientists to "make major contributions to defense applications, space and astrophysical plasma physics, materials science, applied mathematics, computer science, and other fields."[6]

Advancing Science and Technology

Many high-technology R&D programs produce secondary benefits or "spin -offs." Spin-offs are not unique to particular fields of research, since extending the frontiers of practically any technology can lead to external applications. Although spin-offs may benefit society, they are unanticipated results of research and should not be viewed as a rationale for continuing or modifying high-technology research programs. Spin-offs may not be efficient mechanisms of developing new or useful technologies, compared to programs dedicated specifically to those purposes. Moreover, applications of new technologies are often drawn from several fields and may not be attributable to any particular one.

Over the years, fusion research has contributed to a variety of spin-offs in other fields. While the program cannot claim sole credit, each of the innovations listed below has at least one key element that came from the fusion program.[7]

[5] Energy Research Advisory Board, *Review of the National Research Council Report: Physics Through the 1990s,* prepared by the Physics Review Board for the U.S. Department of Energy, February 1987, p. 44.

[6] Ronald C. Davidson, "Overview of Magnetic Fusion Advisory Committee Findings and Recommendations, " presentation to Energy Research Advisory Board Fusion Panel, Washington, DC, June 25, 1986.

[7] This list is drawn from three reports: U.S. Department of Energy, Office of Energy Research, *Technology Spin-offs From the Magnetic Fusion Energy Program,* DOE/ER-01 32, May 1982; U.S. Department of Energy, Office of Fusion Energy, *Technology Spinoffs From the Magnetic Fusion Energy Program,* DOE/ER-01 32-1, February 1984; and U.S. Department of Energy, Office of Energy Research, *The Fusion Connection,* DOE/ER-0250, October 1985. For more information about the role of these technologies and others in magnetic fusion research, see ch. 4.

Contributions to Industry

Certain phenomena associated with fusion research have proven particularly applicable to the development of electronic systems and industrial manufacturing processes. *Plasma etching* is an important process in the semiconductor industry. Fusion research has provided information necessary to characterize and understand the process more completely and also has contributed plasma diagnostics that can be used to monitor the etching process.

Microwave electronics is another fusion contribution that has both civilian and military applications. Microwave tubes and plasmas share certain physical principles of operation, and advances in the understanding of basic plasma physics have contributed to improvements in microwave technology. The fusion program has also fostered development of the microwave industry through its requirements for high-frequency, high-power microwave sources, such as the gyrotron. Typical applications of microwave technology include high-power radar stations, television broadcasting, satellite communications, and microwave ovens.

Plasma physics phenomena studied in the fusion program also have significant applications i n the plasma coating and surface modification of industrial materials. Plasma *coating* is important to the manufacturing industry because it may enable materials to better resist wear and corrosion. Finally, fusion experimental facilities use sophisticated power-handling technologies; electric utilities are interested in the near-term applications of these technologies.

Contributions to National Defense

Although magnetic fusion research has no direct application to military uses, the fusion program has contributed to the national defense. The most valuable contributions are in the background plasma physics research conducted by the fusion program and the education of scientists that later are hired by defense programs. in addition, many scientific ideas and technological developments being investigated under the Strategic Defense Initiative (SDI) grew out of research in the fusion program. For example, contributions made by the magnetic fusion program in the development of neutral beams and accelerators for free electron lasers have been instrumental to the development of directed-energy weapons necessary for SDI applications.

Contributions to Basic Science

Plasma physics is by now considered one of the core areas of physics research. Advances made in the fusion program in the understanding of plasma phenomena have been used by NASA, the Department of Defense (DoD), and others. Moreover, the fusion program has supported basic atomic physics research for more than two decades in order to develop detailed knowledge of fundamental atomic and molecular processes influencing plasma behavior.

Magnetic fusion research requires computational methods and facilities that are not available in other disciplines. Thus, the magnetic fusion program leads the way in the acquisition and use of state-of-the-art computers. The Magnetic Fusion Energy Computing Center's (MFECC) system of Cray computers and the satellite network system installed for these computers are important advances in computer technology. In addition, the fusion program has developed advanced computational methods in order to model and analyze plasma behavior.

Finally, fusion research has contributed to the development of plasma diagnostic technologies that have commercial, scientific, and defense applications. The demands of fusion research on diagnostic instrumentation are extremely exacting. Not only are plasmas very complex phenomena, but measurements of their characteristics must be made from the outside of the plasma so as not to affect it. Therefore, considerable development of sophisticated instrumentation has been required throughout the history of fusion research.

Stature

The stature of the United States abroad benefits from conducting high-technology research. The United States has been at the forefront of fusion R&D since the program was initiated in the

1950s. Maintaining a first-rate fusion program has placed the United States in a strong bargaining position when arranging international projects, has attracted top scientists from other fusion programs to the United States, and has enhanced the reputation of the United States in scientific and technical programs other than magnetic fusion.

NEAR-TERM COSTS

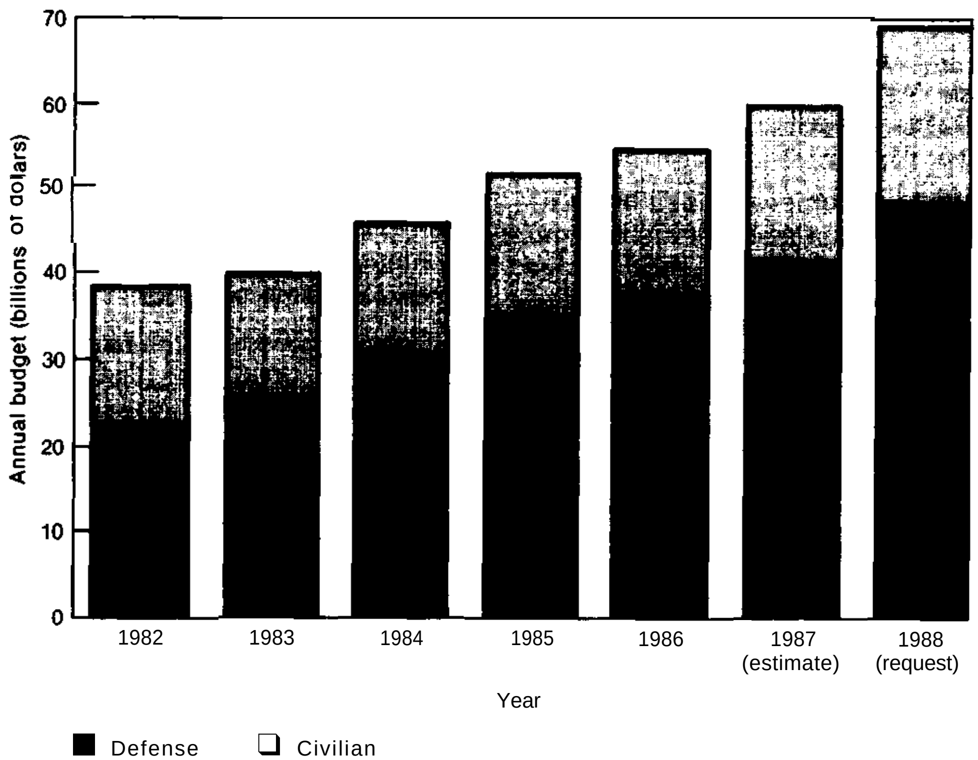
Magnetic Fusion Funding

The fusion program utilizes both financial and personnel resources. This section analyzes the monetary cost of fusion research by providing a sense of context for fusion expenditures. Fusion expenditures are compared to other government R&D programs and to energy R&D programs in particular.

Comparing Fusion to Other Government R&D

The Federal budget for R&D has grown steadily during the 1980s, in real terms. The bulk of this growth has been driven by increases in defense R&D spending, which almost doubled between 1982 and 1987. Non-defense R&D has also grown, though only 15 percent over the same period (see figure 6-2).

Figure 6-2.-Defense and Civilian Federal R&D Expenditures (in current dollars)

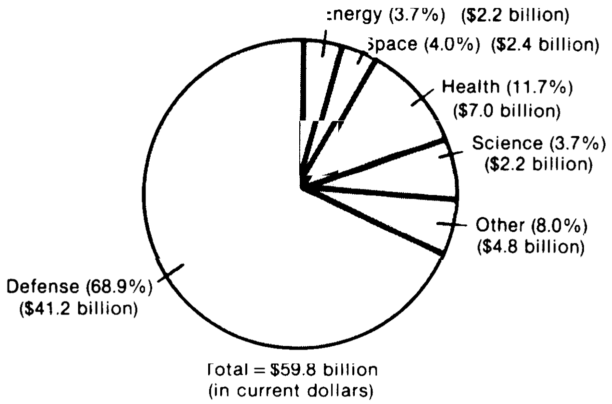


Defense: **Department of Defense along with Department of Energy atomic energy defense activities.**

Civilian: **All other Federal R&D activities.**

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: 1987).

Figure 6-3.–Major Components in Federally Funded R&D in Fiscal Year 1987



Defense: Includes Department of Defense along with Department of Energy atomic energy defense activities.

Health: Includes health research in the Department of Health and Human Services, Veterans Administration, Department of Education, and the Environmental Protection Agency.

Space: Includes the National Aeronautics and Space Administration, less space applications and aeronautical research (which are included in the "Other" category).

Energy: Includes energy research in the Nuclear Regulatory Commission, Environmental Protection Agency, and Department of Energy, less general science and defense expenditures.

Science: Includes National Science Foundation and Department of Energy general science (high energy physics and nuclear physics).

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: 1987).

Figure 6-3 shows the estimated fraction of the Federal research budget dedicated to various areas during FY 1987, and figure 6-4 depicts historical budget levels among these areas. It is estimated that the defense program will receive the largest portion, almost 70 percent, of Federal R&D funding in FY 1987. DoD will fund over 90 percent of this research, with the remainder funded by DOE. In FY 1987, defense-related activities will utilize one-half of DOE's R&D funding.

The next largest identifiable blocks of Federal R&D funding, each of approximately equal size, are space, health, energy, and general science research. Space activities are conducted by NASA. Most health-related research is conducted by the Department of Health and Human Services, through the National Institutes of Health (NIH). Most general science research is carried out by the National Science Foundation (NSF) and DOE's high energy physics and nuclear physics programs. DOE conducts most Federal energy R&D; the Nuclear Regulatory Commission and the Environmental Protection Agency also conduct limited energy research.

Those Federal R&D programs with budget authority estimated at over $200 million in FY 1987 are listed in table 6-1.[8] The intent of this table is to provide a context for the fusion program by depicting its relative funding commitment. The table is not intended to compare the magnetic fusion program to other programs, because the programs listed are not directly comparable. Some are near-term efforts; others—like fusion—are very long-term. Some, also like magnetic fusion, are focused on a single primary application; others, like the cancer research conducted by NIH, encompass a wide range of smaller subprograms. The balance between research and development varies considerably as well. DoD's large research, development, and testing programs include a small amount of research and a great deal of development and testing, whereas NSF's programs, for example, are almost entirely pure research.

As the table shows, the largest Federal R&D programs are defense-related. Magnetic fusion is DOE's fifth largest R&D program, following weapons R&D and testing, naval reactor development, high energy physics, and basic energy sciences.

Although table 6-1 provides a sense of scale between magnetic fusion research and other Federal R&D programs, it cannot be used to compare the programs themselves or the decisions by which these programs are funded. The criteria by which funding decisions are made in different agencies and departments are not consistent, and the degree of competition for funds between programs–either within a specific office or between offices, agencies, or departments—is difficult to measure. The budgets of different programs are prepared separately within the executive branch and considered separately in Congress.

[8] A distinction is made between Budget Authority and Budget Outlay. Budget authority denotes how much a program could spend. In some cases, however, actual budget outlays (what the program did spend) will differ from the budget authority. A program may spend less than its budget authority, or more if it has accrued savings from previous years.

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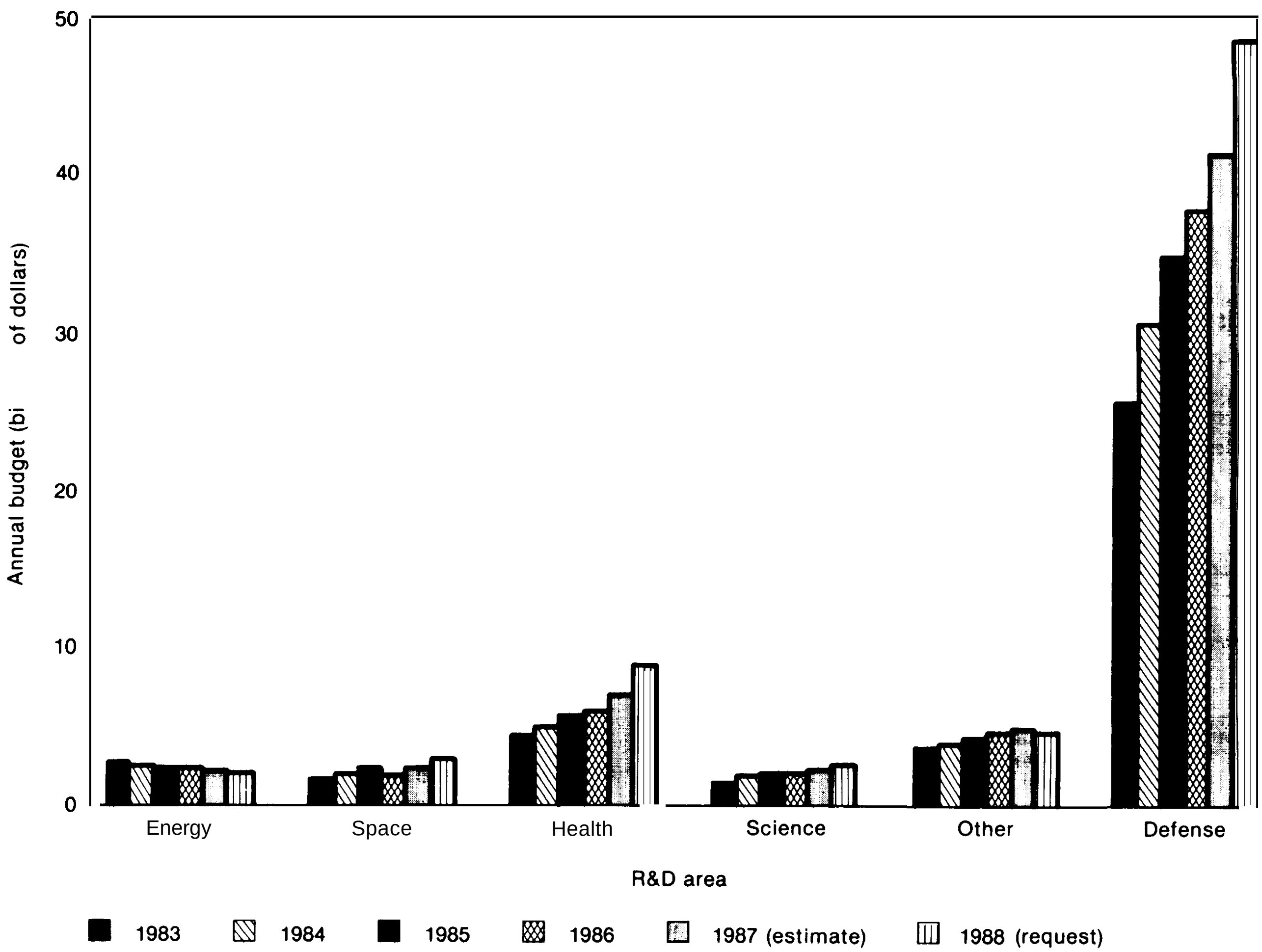
Figure 6=4.—Historical Component Funding Levels of Federal R&D Programs (in currant dollars)



SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: 1987).

Overall comparisons of one program to another are typically made only at the highest levels of aggregation, if at all.

In addition, this table does not represent a complete picture of all research undertaken by the U.S. economy. It only measures Federal investments, and in many programs there is substantial private sector involvement. Total private sector investment in R&D activities for 1987 is estimated at $60 billion, about the same as Federal R&D investment for that year. g

[9]National Science Foundation, Division of Science Resources Studies, *Science and Technology Data Book 1987* (Washington, DC: National Science Foundation, 1986), NSF-86-31 1, figure 1, p. 3.

Comparing Fusion to Energy R&D

Since 1980, significant shifts in the emphasis of DOE appropriations have occurred. The department has focused more heavily than it did previously on atomic energy defense activities and less heavily on activities conducted by civilian programs, while overall DOE appropriations have decreased. Thus, civilian programs have competed for a smaller piece of a shrinking pie, resulting in serious financial pressure on civilian energy R&D. This shrinkage is in large part due to the Reagan Administration policy that development of near-term technology for civilian applications is better left to the private sector.

Table 6-1 .—Federally Funded R&D Programs With Budget Authority Over $200 Million in Fiscal Year 1987

Research and development program name	Fiscal year 1987 budget estimate[a] (millions)
Department of Defense	$ 38,374.5
Army	($ 4,754.6)
Navy	($ 9,381.9)
Air Force	($ 15,416.8)
Defense agencies	($ 7,185.5)
Strategic Defense Initiative	[$ 3,743.4]
Defense Advanced Research Projects Agency	[$ 785.2]
Office, Secretary of Defense	[$ 569.1]
Defense Nuclear Agency	[$ 306.0]
National Aeronautic and Space Administration	$ 3,127.7
Space Station	($ 420.0)
Space Transportation Capability Development	($ 495.5)
Space Science and Applications	$ 1,552.6)
Physics and Astronomy	552.8]
Planetary Exploration	[$ 358.4]
Environmental Observations	[$ 320.9]
Aeronautics and Space Technology	($ 592.0)
Aeronautical research and technology	[$ 376.0]
Department of Energy	$ 5,561.1
Energy Supply R&D	($ 1,498.6)
Basic Energy Sciences	[$ 470.6]
Magnetic Fusion	[$ 345.3]
Nuclear Energy	[$ 325.9]
General Science and Research	($ 716.8)
High Energy Physics	[$ 499.7]
Nuclear Physics	[$ 217.1]
Atomic Energy Defense Activities	($ 2,785.7)
Weapons R&D and Testing	[$ 1,882.2]
Naval Reactors Development	[$ 563.8]
Department of Health and Human Services	$ 6,709,8
Alcohol, Drug Abuse and Mental Health Administration	($ 569.4)
General Mental Health	[$ 307.5]
National Institutes of Health	($ 5,853.2)[b]
Cancer	[$ 1,371 .5]
Heart, Lung, and Blood	[$ 891 .2]
Allergy and Infectious Diseases	[$ 535.6]
Diabetes, Digestive and Kidney Diseases	[$ 488.2]
Neurological and Communicative Diseases and Stroke	[$ 476.5]
Child Health and Human Development	[$ 352.5]
Eye	[$ 211 .1]
Environmental Health Sciences	[$ 200.4]
National Science Foundation	$ 1,520.3
Mathematical and Physical Sciences	($ 463.4)
Biological, Behavioral, and Social Sciences	($ 257.7)
Geosciences	($ 284.6)
Department of Agriculture	$ 1,027.5
Agricultural Research Service	($ 523.3)
Cooperative State Research Service	($ 300,3)
Department of Interior	$ 362.2
Geological Survey	($ 208.6)
Department of Transportation	$ 285.2
Department of Commerce	$ 401.6
National Oceanic and Atmospheric Administration	($ 287.5)
Environmental Protection Agency	$ 343.4
Veterans Administration	$ 225.3
Agency for International Development	$ 224.2

aValues denoted with "( )" comprise programs included within the preceding department total. and values denoted with "[ ]" comprise subprograms included within the preceding program total Only departments, programs, and subprograms with an annual budget over $200 million are listed; therefore, the listed program and subprogram budgets may not total the preceding departmental or program budget

bTotal program budget given for the National Institutes of Health Includes an overall reduction of $67.1 million, which has not been allocated among individual Institute subprogram budgets in these figures

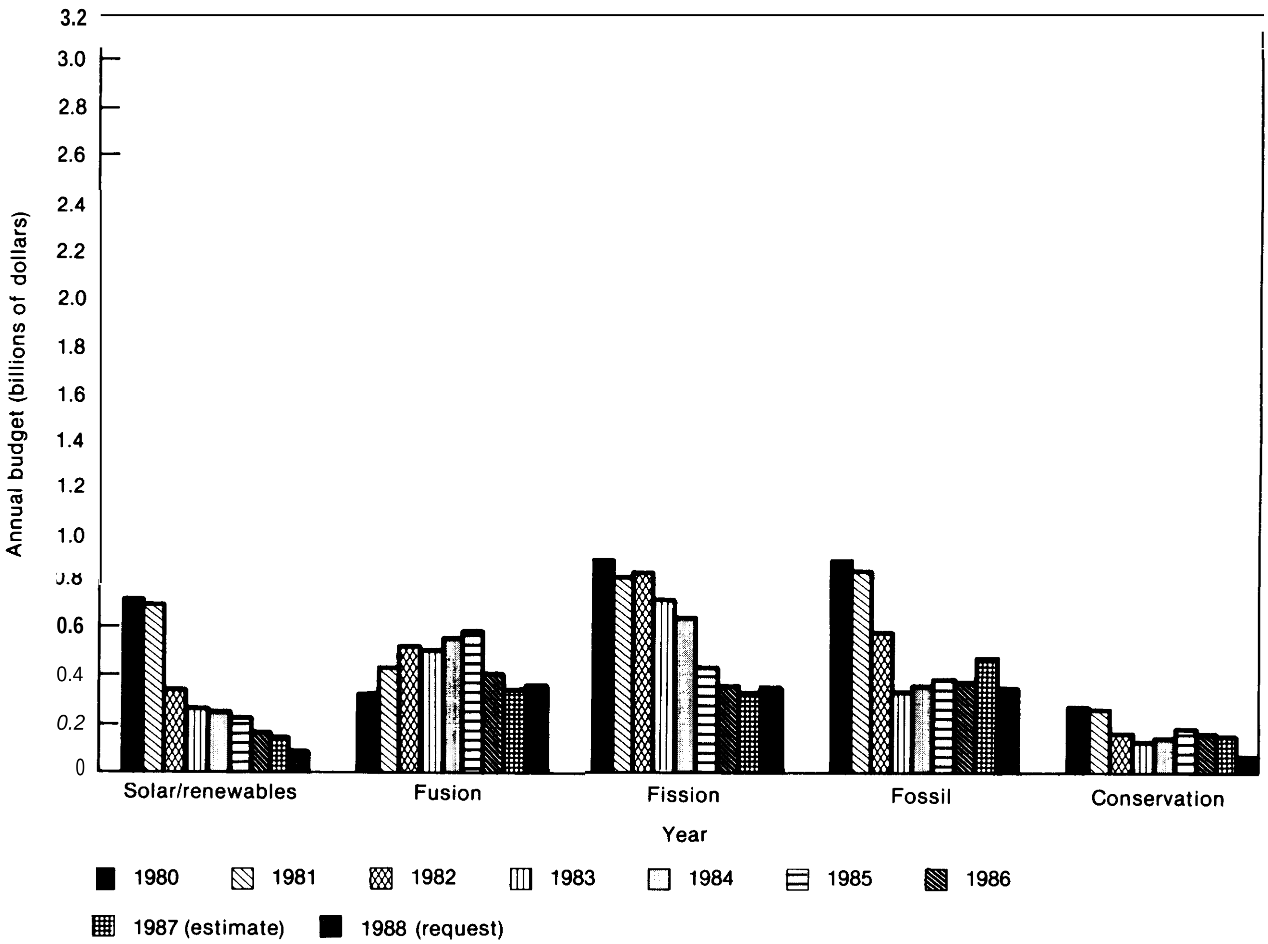
SOURCE American Association for the Advancement of Science, Intersociety Working Group, AAAS *Report XII: Research and Development FY 1988* (Washington, DC American Association for the Advancement of Science, 1987)

Though magnetic fusion has fared better than many other energy programs, its budget has fallen significantly in recent years. From a peak of $659.7 million in FY 1977 (in 1986 dollars), funding for the fusion program has declined by over half, to a level of $319.1 million in FY 1987 (in 1986 dollars) .10 Figure 6-5 illustrates the recent budgets of DOE's larger energy R&D programs.

Unlike short-term energy development, the long-term, high-risk nature of the fusion energy program satisfies the criteria of the Reagan Administration's science and technology policy. Long-term, research-oriented programs like fusion have been able to maintain Federal budgetary support because, although there is a potentially high payoff, there is currently little incentive

[10] Budget values and inflation indices were provided by J. Ronald Young, Director of the Office of Management, U.S. Department of Energy, Off Ice of Energy Research, letter to the Office of Technology Assessment, Aug. 15, 1986.

Figure 6-5.—Annual Appropriations of DOE Civilian R&D Programs (in current dollars)



SOURCE: Argonne National Laboratory, *Analysis of Trends in Civilian R&D Appropriations for the U.S. Department of Energy*, 1986.

for industrial involvement. Even if the risks were not high, the benefits are so far off that their present value is not sufficient to interest private investors today. Virtually all fusion research is funded by the Federal Government. DOE's programs in nuclear energy, fossil fuels, conservation, and renewable energy, on the other hand, have lost much of their Federal support because it is believed that industry financing is appropriate in these cases.

Costs of Fusion Facilities

Table 6-2 lists the total construction costs of some representative fusion program experiments.[11]

[11] For information about the technical details of many of these projects, see ch. 4.

The most expensive fusion projects to date are the Tokamak Fusion Test Reactor (TFTR) and the Mirror Fusion Test Facility (MFTF-B), which are an order of magnitude more expensive than other confinement experiments. In part, TFTR and MFTF-B were more expensive than other experiments because they required development of an extensive supporting infrastructure as well as construction of the actual device. In addition, these facilities are more advanced and much larger than the experiments constructed on alternative concepts.

The next facility the U.S. fusion program plans to construct, the Compact Ignition Tokamak (CIT), has an estimated cost of $360 million. It is proposed to be built at Princeton Plasma Physics

Table 6-2.—Cost of Representative Fusion Experiments

Experiment	Location	Type	Construction cost (millions of 1987 dollars)
Tokamak Facility Test Reactor	PPPL	Tokamak	$562
Mirror Fusion Test Facility-B	LLNL	Tandem Mirror	$330
Doublet III	GA	Tokamak	$ 56[a]
Doublet III-D (Upgrade)	GA	Tokamak	$ 36[a]
International Fusion Superconducting Magnet Test Facility	ORNL	Magnet Test[b]	$ 36[c]
Poloidal Divertor Experiment	PPPL	Tokamak	$ 54
Princeton Large Torus	PPPL	Tokamak	$ 43
Tritium Systems Test Assembly	LANL	Tritium Test[b]	$ 26
Tandem Mirror Experiment	LLNL	Tandem Mirror	$ 24
Tandem Mirror Experiment Upgrade	LLNL	Tandem Mirror	$ 23
Texas Experimental Tokamak	UT	Tokamak	$ 21
Advanced Toroidal Facility	ORNL	Stellarator	$ 21
TARA	MIT	Tandem Mirror	$ 19
ZT-40	LANL	Reversed-Field Pinch	$ 17
Alcator C	MIT	Tokamak	$ 15
Rotating Target Neutron Source	LLNL	Materials Test[b]	$ 11
Impurity Studies Experiment-B	ORNL	Tokamak	$ 5
Field Reversed Experiment-C	LANL	Field-Reversed Configuration	$ 3
Phaedrus	UW	Tandem Mirror	$ 1.8
Macrotor	UCLA	Tokamak	$ 1.5
IMS	UW	Stellarator	$ 1.4
Tokapole	UW	Tokamak	$ 0.6

KEY PPPL—Princeton Plasma Physics Laboratory, Princeton, New Jersey
LLNL—Lawrence Livermore National Laboratory, Livermore, California
ORNL—Oak Ridge National Laboratory, Oak Ridge, Tennessee
GA—GA Technologies, Inc. San Diego, California
LANL—Los Alamos National Laboratory, Los Alamos, New Mexico
UT—University of Texas, Austin, Texas
MIT—Massachusetts Institute of Technology, Cambridge, Massachusetts
UW—University of Wisconsin, Madison, Wisconsin
UCLA—University of California, Los Angeles, California

[a]Values shown for the combined Doublet III facility and upgrade do not Include an additional $54 million (in current dollars) of hardware provided by the government of Japan or $36 million (in 1987 dollars) for a neutral beam addition

[b]These facilities are fusion technology facilities; all others on the table are confinement physics experiments.

[c]The cost of this facility does not include the cost of the six magnet coils that are being tested there. It is estimated that the magnet coils cost between $12 million and $15 million each (in current dollars)

SOURCE US Department of Energy, Office of Fusion Energy, 1987

Laboratory, where it can take advantage of the lab's existing infrastructure. With initial construction funds requested in the FY 1988 DOE budget, CIT will be the largest fusion project undertaken in recent years.

Looking beyond CIT, the U.S. fusion program sees a next-generation engineering test reactor as necessary during the 1990s. Funding for this device, which is projected to cost well overabillion dollars, has not been requested by or appropriated to DOE. A recent DOE proposal to undertake international conceptual design and supporting R&D is currently being considered. If successful international construction and operation of the device could follow the design phase of the project (see ch. 7).

Magnetic Fusion Personnel

The fusion program currently supports approximately 850 scientists (almost all Ph.D.s), 700 engineers, and 770 technicians.[12] These researchers work primarily at the national laboratories and in the university and college fusion programs. Because the size of the labor pool responds to shifts in the demand for labor, and because the long-term value of having a person work on one pro-

[12]Thomas G. Finn, U.S. Department of Energy, Office Of Fusion Energy, letter to the Office of Technology Assessment, Mar. 12, 1987. The number of technicians represents only full-time staff associated with experiments; shop people and administrative staff are not included. Figures for scientists and engineers include university professors and post-doctoral appointments; graduate student employees are not included.

gram as opposed to any other is difficult to measure, it is hard to quantify the implications of dedicating scientific and engineering manpower to the fusion program. The value of the fusion program for training plasma physicists, however, cannot be denied. **The fusion program trains far more people than it employs, and these people make valuable contributions in a variety of fields other than fusion.**

According to DOE, since 1983 the number of Ph.D. staff positions at the major national fusion research centers has declined by almost 20 percent. Personnel levels among individuals without Ph.D.s, and the staffs of smaller fusion research centers, have also declined substantially. A recent study for the National Academy of Sciences predicts that if recent funding trends continue, the fusion program could lose 345 Ph.D.s between 1985 and 1991. Most fusion researchers who have left the fusion program have found work easily in other research programs within DOE and DoD. Many former fusion researchers are working on SDI. As the mobility of fusion researchers shows, these individuals have skills that are in demand in many areas.

PARTICIPATION IN MAGNETIC FUSION RESEARCH

DOE's Office of Fusion Energy (OFE) funds research conducted by three different groups: national laboratories, colleges and universities, and private industry. Each of these groups has different characteristics, and each plays a unique role in the fusion program.

Department of Energy National Laboratories

DOE's national laboratories play an important role both in the fusion program and in the department's general energy R&D. Figure 6-6 depicts DOE's distribution of laboratory funding among various subject areas. A list of DOE's major national laboratories, showing the extent of their fusion participation, is shown in table 6-3.

National laboratories are generally government-owned, contractor-operated facilities. Most of them were created during or shortly after World War II to conduct research in nuclear weapons and nuclear power development. Four DOE national laboratories have major research programs in magnetic fusion. It is estimated that these laboratories will conduct over 70 percent of the magnetic fusion R&D effort in FY 1987. According to DOE, the laboratories "are a unique tool that the United States has available to carry on the kind of large science that is required to address certain problems in fusion. " It is expected that the involvement of the national laboratories in the research program will remain important at least until the technology is transferred to the private sector for commercialization. The four major fusion laboratories are described below, in decreasing order of their share of the FY 1987 fusion budget.

Princeton Plasma Physics Laboratory

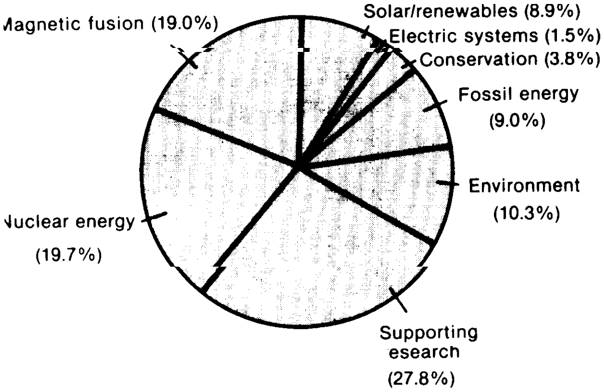
The Princeton Plasma Physics Laboratory (PPPL), located in Princeton, New Jersey, is one of the fusion program's oldest and most important facilities. It is located on Princeton University's James Forrestal Campus, and, in FY 1987, PPPL is estimated to receive the largest share of DOE's magnetic fusion budget of any single institution (27 percent).[14] PPPL is a program-dedicated laboratory, which means that virtually all of its research involves magnetic fusion. The bulk of PPPL's budget is used to operate TFTR, the largest U.S. tokamak experiment. TFTR is one of two operational experiments in the world designed to burn D-T fusion fuel, the other being the European Community's Joint European Torus.[15] In addition to TFTR, PPPL operates other smaller tokamak experiments.

[13] John F. Clarke, Director, DOE Office of Fusion Energy, ' 'planning for the Future, ' *Journal of Fusion Energy,* vol. 4, nos. 2/3, June 1985, p, 202.

[14] Based on U.S. Department of Energy, FY 1988 Congression Budget Estimates for Lab/Plant, January 1987.

[15] Princeton Plasma Physics Laboratory, *An Overview. Princeton Plasma Physics Laboratory,* April 1985, p. 5. For more information on TFTR and other experiments, see ch. 4.

Figure 6-6.—Major DOE Civilian R&D Funding at National Laboratories in Fiscal Year 1987



SOURCE: U.S. Department of Energy, Fiscal Year 1988 Congressional Budget Estimates for Lab/Plant, January 1987.

Lawrence Livermore National Laboratory

In FY 1987, it is estimated that Lawrence Livermore National Laboratory (LLNL), located in Livermore, California, will receive 15 percent of DOE's magnetic fusion energy budget.[16] LLNL has concentrated on tandem-mirror systems, and most of the experimental facilities at the laboratory have explored the capabilities of this confinement scheme.[17] The major magnetic fusion facility at LLNL is MFTF-B, a project that was moth balled in 1986, due to budget cuts, just weeks after construction was completed; MFTF-B has never operated. In addition to MFTF-B, there is another significant tandem-mirror facility at LLNL—the Tandem Mirror Experiment Upgrade (TMX-U), which has also been terminated. LLNL is now installing a small tokamak experiment and has been given responsibility for the design of the next-generation engineering test reactor. LLNL also operates the Magnetic Fusion Energy Computing Center for DOE. Moreover, LLNL conducts the largest component of the Nation's inertial confinement fusion research programs (see app. B).

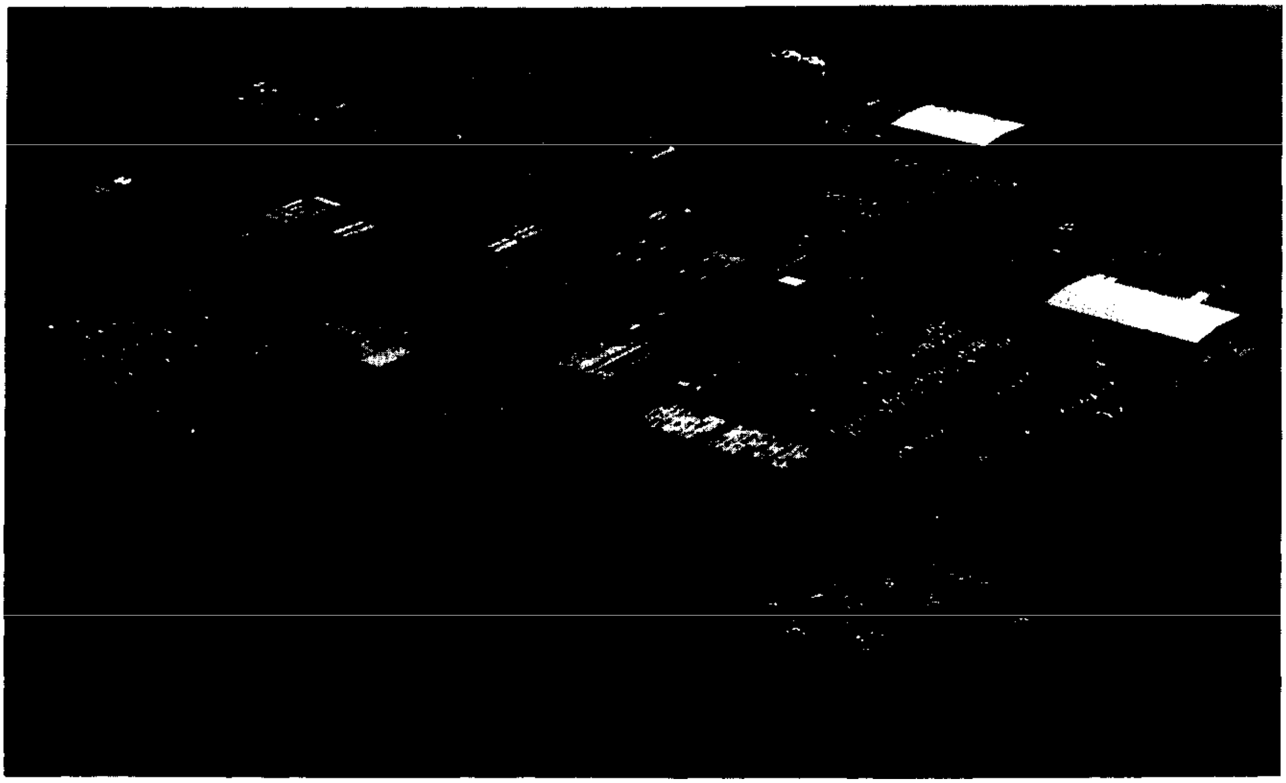
[16] Based on U.S. Department of Energy, FY 1988 Congressional Budget Estimates, op. cit.
[17] For technical information on the tandem m i rror configuration, see ch. 4.

Table 6.3.—DOE'S Major National Laboratories

Laboratory	Location	Magnetic fusion research
Ames Laboratory	Ames, IA	None
Argonne National Laboratory	Argonne, IL	Minor
Bettis Atomic Power Laboratory	West Mifflin, PA	None
Brookhaven National Laboratory	Upton, NY	None
Fermi National Accelerator Laboratory	Batavia, IL	None
Hanford Engineering Development Laboratory	Richland, WA	Minor
Idaho National Engineering Laboratory	Idaho Falls, ID	Minor
Knolls Atomic Power Laboratory	Schenectady, NY	None
Lawrence Berkeley Laboratory	Berkeley, CA	Minor
Lawrence Livermore National Laboratory	Livermore, CA	Major
Los Alamos National Laboratory	Los Alamos, NM	Major
Mound Laboratory	Miamisburg, OH	None
Nevada Test Site	Mercury, NV	None
Oak Ridge National Laboratory	Oak Ridge, TN	Major
Pacific Northwest Laboratory	Richland, WA	Minor
Paducah Gaseous Diffusion Plant	Paducah, KY	None
Pinellas Plant	St. Petersburg,	None
Portsmouth Gaseous Diffusion Plant	Piketon, OH	None
Princeton Plasma Physics Laboratory	Princeton, NJ	Major
Rocky Flats Plant	Golden, CO	None
Sandia National Laboratory	Albuquerque, NM	Minor
Savannah River Plant	Aiken, SC	None
Stanford Linear Accelerator Laboratory	Stanford, CA	None

KEY: None - No magnetic fusion funding.
Minor - Fusion funding is less than $10 million in fiscal year 1987.
Major - Fusion funding is more than $10 million in fiscal year 1987.

SOURCE: Office of Technology Assessment, 1987.



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Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL), located in Oak Ridge, Tennessee, conducts research across the full range of magnetic fusion program activities and is actively involved with national and international cooperation in virtually every area. The Advanced Toroidal Facility (ATF), when complete, will be ORNL's main experiment in toroidal confinement. It is anticipated that ATF, a stellarator, will make important contributions to the improvement of toroidal systems by increasing the understanding of fundamental confinement physics.[18] Contributing to this understanding are other ORNL programs in theory, diagnostics, and atomic physics The ORNL technology program is fusion's largest, and it includes plasma heating and fueling, superconducting magnets, materials, and environmental assessment programs. In addition, ORNL is the host for the Fusion Engineering Design Center, which supports both reactor and next-generation device studies throughout the program. It is estimated that ORNL will receive about 15 percent of the magnetic fusion energy program's budget in FY 1987.[19]

Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) is located in Los Alamos, New Mexico, and it contributes to DOE's fusion energy program in several ways. LAN L has focused on alternative concepts. These concepts, not as far developed as the tokamak or mirror, are studied in several experiments at Los Alamos that are smaller and therefore less expensive than the large tokamak and mirror ma-

[18] See ch. 4 for a technical description of the stellarator confinement concept.

[19] U.S. Department of Energy, FY 1988 Congressional Budget Estimates, op. cit.

Photo credit: Oak Ridge National Laboratory

Assembly of The Advanced Toroidal Facility at Oak Ridge National Laboratory.

chines.[20] In addition, LANL conducts research in fusion technology and materials, studies reactor systems, and operates the Tritium Systems Test Assembly (TSTA)—a prototype of the tritium-handling apparatus necessary to fuel a D-T fusion reactor. In FY 1987, LANL will receive about 7 percent of the magnetic fusion energy program's budget.[21]

[20] Refer to ch. 4 for technical information on alternative confinement concepts.

[21] U.S. Department of Energy, FY 1988 Congressional Budget Estimates, op. cit.

Universities and Colleges

Role in the Research Program

Universities and colleges contribute to many areas of energy research, including magnetic fusion. The role of these programs in fusion R&D activities differs significantly from the role of the national laboratories. Universities and colleges provide education and training and have been historically a major source of innovative ideas as well as scientific and technical advances. These programs could not replace the national labora-

m m N ry

b d m Am g h o b o
h p g m d p h h d pm h h gh d k m k p
g p m d h d d b p h h w b d C h d
om h mp h p m pm p g d h d opm
b h o How d g d g o h o g dd
p g m h m d q d mp rt p g m h m d mp
b h h b m

cepts. Overall, the Magnetic Fusion Advisory Committee (MFAC) Panel V found:

> The contributions from university-based experimental programs over the past decade have been significant, obviously cost-effective and have had a major impact on the development of fusion energy in general, and the large-scale or "mainline" experiments at the national laboratories in particular.[22]

University and college fusion programs also educate the young researchers in the field.

table 6-4 lists the university and college fusion programs. It is estimated that these programs collectively will receive over 14 percent of the magnetic fusion budget in FY 1987 directly from DOE. In addition, university and college fusion programs could receive another 2 to 3 percent of

[22] Magnetic Fusion Advisory Committee Panel V, *Principal Findings and Recommendations of the Magnetic Fusion Advisory Committee Subpanel Evaluating the Long-Term Role of (Universities in the Fusion Program,* July 1983, p. 18. The Magnetic Fusion Advisory Committee is a committee of fusion scientists and engineers that provide technical advice to DOE's Office of Fusion Energy.

Table 6-4.—Universities and Colleges Conducting Fusion Research in Fiscal Years 1983 and 1986 (in 1986 dollars)

University or college	Fiscal year 1983 budget authority	Fiscal year 1986 budget authority
Massachusetts Institute of Technology	$26.6 million	$24.6 million
University of Texas	$ 6.9 million	$ 5.4 million
University of California—Los Angeles	$ 4.1 million	$ 6.2 million
University of Wisconsin	, $ 4.1 million	$ 4.8 million
University of Maryland	$ 1.9 million	$ 983,000
New York University	$ 1.3 million	$ 1.1 million
Columbia University	$ 1.1 million	$ 1.2 million
University of Washington	$ 776,000	$ 708,000
Cornell University	$ 760,000	$ 535,000
University of California—Berkeley	$ 618,000	$ 438,000
Johns Hopkins University	$ 483,000	$ 340,000
University of California—Irvine	$ 481,000	$ 147,000
Rensselaer Polytechnic Institute	$ 353,000	$ 392,000
California Institute of Technology	$ 351,000	$ 503,000
Georgia Institute of Technology	$ 271,000	$ 115,000
Pennsylvania State University	$ 263,000	$ 97,000
University of California—Santa Barbara	$ 241,000	
University of Illinois	$ 226,000	$ 335,000
Auburn University	$ 212,000	$ 372,000
University of Missouri	$ 201,000	$ 239,000
University of California—San Diego	$ 175,000	$ 240,000
Yale University	$ 123,000	$ 50,000
University of Arizona	$ 115,000	$ 13,000
College of William and Mary	$ 95,000	$ 18,000
University of Connecticut	$ 90,000	$ 80,000
Western Ontario University	$ 78,000	—
University of Michigan	$ 66,000	
Wesleyan University	$ 63,000	$ 50,000
Stanford University	$ 60,000	$ 13,000
University of Iowa	$ 30,000	—
University of Virginia	$ 30,000	—
State University of New York—Buffalo	$ 24,000	
Dartmouth College	$ 14,000	$ 60,000
University of Colorado	—	$ 60,000
North Carolina State University	—	
Stevens Institute of Technology	—	$ 15,000
Syracuse University	—	$ 101,000
University of New York City	—	$ 25,000
Total university and college budget	$52,322,000 (33 programs)	$49,301,000 (30 programs)

SOURCE: Fiscal year 1983 budgets from Magnetic Fusion Advisory Committee Panel V, Principal Findings and Recommendations of the MFAC Subpanel Evaluating the Long-Term Role of Universities in the Fusion Program, July 1983, p. 9 Fiscal year 1986 budgets provided by DOE's Office of Fusion Energy, FY 1988 Congressional Budget Contractor Summary, Jan 16, 1987 the fusion budget indirectly through subcontracts from the national laboratories. The programs conducted by the universities in fusion are diverse, varying in funding level and research area. Over 80 percent of the university programs received less than $1 million each from DOE in FY 1986.

Recent budget cuts have seriously affected university and college fusion programs, which have suffered larger percentage budget reductions than the fusion program as a whole. University funding was $49.3 million in FY 1986, is estimated at $44.7 million in FY 1987, and is requested to be $41.7 million in FY 1988, in current dollars. The last two figures represent percentage decreases of 9 and 7 percent, respectively.[23] The corresponding decreases for the overall fusion budget ($361.5 million in FY 1986, an estimated $341.4 million in FY 1987, and a requested $345.6 million in FY 1988, in current dollars) are 6 percent and – 1 percent.

For university and college fusion programs, DOE is the only source of financial support. NSF, the other likely Federal support agency, does not fund fusion research because it is considered applied, as opposed to basic, research and because it is believed to be DOE's area. Thus, given recent budget cuts, two-thirds of the university and college programs have either reduced or eliminated their programs since 1983. Seven colleges have eliminated their fusion programs, while five new programs have been added. It is anticipated by University Fusion Associates (UFA), an informal grouping of individual fusion researchers from universities and colleges, that if current funding trends continue, as many as half of the colleges and universities will eliminate their fusion research programs between 1986 and 1989.[24] DOE has stated that it intends to maintain the university fusion budget at a constant level (corrected for inflation) and does not foresee any need for additional programs to drop out. In any case, continued tight budgets and the loss of university programs reduces the ability of the fusion program to attract and educate new researchers.

In response to the funding cuts and the narrowing of the fusion program's scope, UFA has recommended that "approximately 3 to 5 percent additional funding should be added back into the fusion budget to support innovative and new ideas."[25] According to UFA, one of the most urgent uses of this money would be to provide seed money to innovative research proposed by universities, national laboratories, and private industry. UFA contends that this funding would help preserve some of the small university programs endangered by budget cuts, as well as create the atmosphere of excitement necessary to attract top students to the field. This idea has been endorsed by other members of the fusion community.

Given recent budgets, university and college fusion programs are concerned about the future direction of DOE's fusion program. In particular, representatives of UFA worry that the role of university fusion programs may be difficult to preserve if the Federal fusion program becomes more dependent on international cooperative projects. The international activities of college and university fusion programs are generally small-scale, and it is not clear how these activities could fit in a collaborative engineering test reactor effort.

University and College Activities

Universities and colleges have made contributions to fusion research in a variety of areas. In tokamak development, university fusion programs have worked on radiofrequency heating and current drive, boundary physics, high beta stability, and transport of heat and particles in fusion plasmas.[26] The largest university tokamak experiments are MIT's Alcator project, the Texas Experimental Tokamak (TEXT) experiment at the University of Texas, and Macrotor at the University of California at Los Angeles (UCLA).

[23] If the Massachusetts Institute of Technology (MIT), the largest university fusion program, is not included, the university fusion budget decreases in FY 1987 and FY 1988 are 7 and 2 percent, respectively.

[24] George H. Miley, testimony on *Fiscal Year 1987 Department of Energy Authorization (Magnetic Fusion Energy),* Hearings before the Subcommittee on Energy Research and Production, House Science and Technology Committee, 99th Cong., 2d sess., vol. 5, Feb. 26, 1986, p. 103.

[25] Ibid., p. 100.

[26] For more information on the technical aspects of these contributions, see ch. 4.

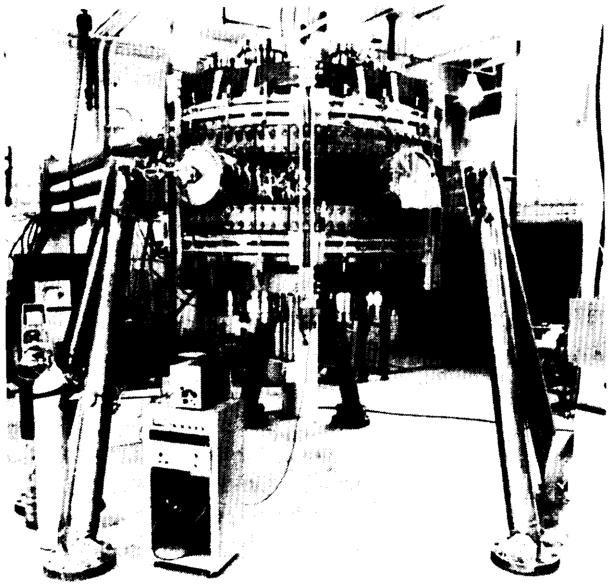

Photo credit: Plasma Fusion Center, MIT

The Alcator C tokamak at the Massachusetts Institute of Technology.

In addition to tokamak research, a small group of universities is exploring the mirror confinement concept. The TARA facility at MIT and Phaedrus at the University of Wisconsin are the major university mirror experiments and, since the moth balling of the mirror machines at LLNL, have become the only U.S. mirror experiments. Support for university mirror programs has decreased, however. In fact, in the budget for FY 1987, DOE proposed elimination of funding for these university-based mirror projects. Congress has made additional funds available to keep both operational throughout FY 1987, and it appears that Phaedrus will remain operational throughout FY 1988 as well.

Several universities also study other confinement concepts for fusion reactors, including the stellarator, compact toroid, and reversed-field pinch. Work in these concepts is conducted at the University of California at Irvine, UCLA, Cornell University, University of Maryland, Pennsylvania State University, University of Illinois, University of Washington, and University of Wisconsin.

Finally, several university programs are exploring technology development and atomic physics. Programs at the University of Arizona, Auburn University, University of California at Santa Barbara, UCLA, Georgia Institute of Technology, University of Illinois, MIT, University of Michigan, Rensselaer Polytechnic Institute, University of Washington, and University of Wisconsin focus on reactor systems, materials, surface effects, and superconducting magnets.

Private Industry

Role in the Research Program

Private industry can take a variety of different roles in fusion research, depending on its level of interest and the stage of development. The most useful roles fall into three main categories.[27] These categories, along with the principal functions performed in each category, are listed in table 6-5.

Industry as Advisor.–The advisory role of private industry is filled frequently by corporate executives who are asked to help assess various stages of program development. The principal benefit of the advisory role is the development of appropriate program goals. As a support services contractor, industry assigns individuals or small groups to work in direct support of a manager at DOE or at a national laboratory. Private industry also provides members of its technical staffs to serve on technical committees, such as

27 Argonne National Laboratory, Fusion Power program, *Technical Planning Activity: Final Report,* commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, 1987, pp. 340-343.

Table 6-5.—Industrial Roles and Functions

Roles	Functions
Advisor	Support services contractor Advisory committee
Direct participant	Materials supplier Component supplier and manufacturer Subsystems contractor Prime contractor, project manager Facilities operator Customer
Sponsor	Research and development

SOURCE: Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final report,* commissioned by the U S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, 1987, table 7-4, p 340 the Magnetic Fusion Advisory Committee (MFAC) or the Energy Research Advisory Board (ERAB). Through advisory arrangements, DOE gains industry's expertise and skills, and industry gains knowledge, contacts, and income. However, there is no commitment in this type of advisory relationship that the advice will be used by DOE or the national laboratories.

Industry as Direct Participant. -To become major participants in the fusion program, industry executives must understand near-term program objectives and be willing and able to contribute to the achievement of these objectives. Industry's direct participation will be particularly important during the engineering phase of the research program, when information and expertise must be transferred to industry from the national laboratories and universities.

As a direct participant, industry can serve a variety of functions. It can supply off-the-shelf components, as well as design and manufacture components made to customer-supplied specifications. One form of direct participation, which industry sees as most valuable, allows the customer (e.g., DOE, a national laboratory, or eventually an electric utility) to define a project and to assign responsibility for the task to a company. Industry can also act as a prime contractor or project manager; in this case, industry is directly responsible to a customer for defined aspects of management, engineering, fabrication, and installation of a product, such as a fusion device or power reactor.

Industry as Sponsor.—The most extensive level of industrial involvement will be the sponsorship of private R&D activities. Sponsorship includes the contribution of direct funds, labor, or both. As a sponsor, industry finances its own research program independently, whereas as a direct participant industry's activities are largely financed by the Federal Government. Sponsoring privately funded R&D requires confidence in the eventual profitability of the technology.

Current Industrial Activities

To date, industrial involvement in fusion research primarily has been advisory, with limited cases of direct participation. Industry representatives serve on the Energy Research Advisory Board and the Magnetic Fusion Advisory Committee, both of which advise DOE on the fusion program. Other industrial participation is facilitated through sub-contracts from national laboratories.

Only one private company, GA Technologies of San Diego, California, participates significantly in fusion research. GA Technologies is a private firm that conducts fusion research under Federal contract. In this sense, GA has been compared to a national laboratory in the field of fusion research. The company became involved in fusion research during the 1950s, when the energy applications of fusion were thought to be closer. Because GA Technologies (then called General Atomic Corp.) was able to assemble a high-quality team of fusion scientists and engineers, the Federal Government has funded the bulk of its fusion research since 1967, when GA lost its primary source of private fusion support. In FY 1987, GA Technologies received 10 percent of DOE's fusion budget.

The fusion program at GA Technologies consists primarily of tokamak confinement research; GA operates the Doublet II I-D (D III-D) tokamak, which is the second largest tokamak in the United States.[28] D II I-D is also the largest U.S. international project. Japan and the United States, through GA Technologies, have jointly financed and operated the D II I-D facility since 1979.[29]

In addition, GA Technologies and Phillips Petroleum Co. invested over $30 million in inventing, fabricating, developing, and operating the Ohmically Heated Toroidal Experiment (OHTE) at GA. OHTE is the only major fusion experiment constructed and operated largely with private funds. OHTE was completed in 1982 and operated until 1985. In 1985, GA and Phillips requested financial support from DOE for further development of the concept. However, DOE would not fund this additional work, initiating a comparable program at LAN L instead. Without

[28] The Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory is about twice as large as D III-D.

[29] For more information on the international cooperation aspects of GA's D II I-D experiment, see ch. 7, pp. 162-163.

Photo credit: GA Technologies

OHTE fusion device at GA Technologies, San Diego, California.

Federal financial support, OHTE was discontinued. In mid-1986, DOE agreed to provide GA with a grant to operate OHTE, and the experiment was restarted. Recently, DOE decided not to renew GA's operating grant for OHTE after FY 1987; it is anticipated that the experiment will be permanently mothballed.

At this stage in the research program, other private companies have found no compelling reason to sponsor fusion research. Even GA Technologies' involvement would be severely limited were it not for extensive Federal funding. Neither are electric utilities currently conducting fusion research. By 1986, the Electric Power Research Institute (EPRI), a utility-funded research organization, had phased out what had been a $4 million per year program. According to the former EPRI fusion manager, EPRI is unwilling to spend money on fusion because the energy applications are so long-range.[30] Individual utilities are not conducting fusion research either, because of the large investment required and the difficulty of convincing regulatory agencies to allow research costs to be transferred to ratepayers.

An MFAC panel on industrial participation in fusion noted that:

> . . . fusion commercialization is sufficiently far in the future and fusion technology sufficiently specialized so that significant cost sharing [between the Federal Government and the private sector] should not be expected. The government and its national laboratories are the immediate customers and should pay the full cost of received products and services. Jl

The position of industry, at least until commercialization is closer, appears to be a subordinate role supporting the national laboratories and universities.

The role of industry in the U.S. fusion program is completely different from its role in the Japanese program, where mechanisms for technology transfer from government to industry have been institutionalized. In Japan, the Japan Atomic Energy Research Institute (JAERI) and various national laboratories and universities conducting fusion research contract with industry to do all the design, research, and development that is necessary. As in the United States, the financial contribution of Japanese industry to fusion research is small. However, its role is critical; according to one JAERI official, the Japanese Government's role is limited to "resolving what type of machine is needed and designing it, " and even this task is "shared" with industry.[32] Thus, Toshiba, Hitachi, and Mitsubishi are intimately involved in fusion research.

In the United States, in contrast, fusion is primarily a government research program. The national laboratories maintain large engineering staffs and have strong manufacturing capabilities.

[30] F. Robert Scott, "Industry and Utility Perspectives on Future Directions in Fusion Energy Development, " *Journal of Fusion Energy,* vol. 5, No. 2, June 1986, p. 138.

[31] Magnetic Fusion Advisory Committee Panel VI I, *Report on Industrial Participation in Fusion Energy Development,* May 1984, pp. 5-2 to 5-3,

[32] Unnamed Japanese official, quoted in Fiona H. Jarrett's *International Collaboration in Magnetic Fusion Energy: The Industrial Role. A Strategy for Industry Participation in an International Engineering Test Reactor Project,* prepared for the U.S. Department of Energy, *Office of* Fusion Energy, August 1986, p. 15.

DOE has only a limited role at present for involving industry in fusion research; industrial participation is typically ad hoc. Due to the budget cuts in recent years, the role of industry has been additionally limited, both because of the few major new projects undertaken and because constricted budgets have made the national laboratories reluctant to subcontract to industry. The role of industry in the U.S. fusion program is not institutionalized.

Establishing an Industrial Base for Fusion

Under current administration policy, the private sector will be responsible for the demonstration and commercialization of fusion technology. As discussed in chapter 5, it is important to establish an industrial capacity on which the private sector can base its development efforts. An MFAC panel on industrial participation in fusion research concluded that:

> . . . if a utility is to invest capital to build a fusion prototype or power plant, it must have confidence in its suppliers. This confidence can be established only if the suppliers have been qualified through active participation in the fusion program and have a record of furnishing quality goods and services.[33]

Currently, there is controversy over how to prepare the industrial base. In particular, **there is extensive disagreement over the timing of industrial participation in the research program prior to the demonstration and commercialization stages.**

For the research phase of fusion development, many fusion scientists contend that industry should be an advisor or low-level direct participant supporting national laboratories and universities. Given the current budget situation and the nature of the research to be completed before demonstration and commercialization, these individuals believe that there are not enough opportunities appropriate for industry to develop and maintain a standing capability in fusion. Moreover, since the private sector is reluctant to invest its own funds, proponents of this position maintain that it is too early in the program to encourage substantial industrial participation. They predict that as demonstration and commercialization approach, industry will naturally become more interested in the applications of fusion technology, hopefully to the point where they are willing to invest money to explore the technology's potential. These individuals believe that limiting industry's participation in the near-term will not preclude its eventual role in demonstration or commercialization; they believe premature industrial involvement could be detrimental.

Others argue that it is essential to involve industry in the research effort before the demonstration stage. The proponents of early industrial involvement stress that technology transfer should occur from the national laboratories and universities to private industry at all stages of the research program, and that such transfer cannot be effective without active industrial participation. The willingness of industry to invest in the technology should not be used as a criteria for determining the appropriate degree of involvement, these people argue, because industry needs information and expertise to accurately assess the value of the technology.

According to these individuals, early involvement of industry and utilities ensures that the technology developed will be marketable by vendors and attractive to its eventual users. Technology transfer will take time; if this transfer is not started until after completion of the research program, fusion's overall development could be delayed. In addition, proponents of this position cite a variety of near-term benefits of industrial participation, including increasing support for the fusion program, facilitating spin-offs from fusion to other technologies, and transferring skills acquired by industries involved in fusion to other areas of high-technology such as aerospace and defense.

The impact of various levels of industrial participation in the research program on the successful commercialization of fusion technology cannot be determined now. Since the mechanisms for transferring responsibility for fusion's development from the Federal Government to the private sector are not yet known, the impact of early

[33] Magnetic Fusion Advisory Committee Panel VII, op. cit., pp. 2-4.

industrial participation on the pace and effectiveness of this transfer is unclear. However, even without linking near-term industrial participation in research to the success of future development, a well-established industrial base must be in place before the private sector can demonstrate and commercialize fusion technology. If the industrial base is insufficient, it will not only be difficult for industry to construct and operate a demonstration reactor, but the customers (probably electric utilities) will be reluctant to purchase fusion reactors.

SUMMARY AND CONCLUSIONS

Fusion research has provided a number of near-term benefits such as development of plasma physics, education of trained researchers, contribution to "spin-off" technologies, and support of the scientific stature of the United States. However, fusion's contributions to these areas does not imply that devoting the same resources to other fields of study would not produce equivalent benefits. Therefore, while near-term benefits do provide additional justification for conducting research, it is hard to use them to justify one field of study over another.

Virtually all of the money spent on fusion research in the United States comes from the Federal Government. The fusion program is DOE's fifth largest research program, and in recent years the program has been relatively well-funded compared to DOE's other energy R&D programs. Nevertheless, the budget for magnetic fusion R&D has fallen by about a factor of 2 since 1977 (in constant dollars). These budget decreases have severely constrained program activities.

Funding limitations have affected the activities of all three major groups that conduct fusion research: national laboratories, universities and colleges, and private industry. Few new construction projects have been initiated in recent years, and research in some areas (particularly mirror fusion) has been curtailed or eliminated. Moreover, many researchers have left fusion. Budget cuts have also interfered with the attainment of the program's near-term goals. In particular, the ability of the fusion program to attract new researchers to its university programs and to train them has suffered. Constrained budgets also limit the participation of industry in fusion research. In addition, the United States is no longer the undisputed leader in fusion research; the Japanese and European fusion programs have caught up with—and may have even surpassed—the U.S. effort.

OTA has not evaluated whether Federal fusion research funds are being spent in the most effective and efficient manner. Neither has it evaluated the appropriate priority to be given to fusion research as compared to other research programs. Comparisons among R&D programs are difficult to make and are typically not made explicitly during the budgetary process. Therefore, comparative funding levels do not necessarily provide an indication of relative priority. The appropriate funding level given to fusion research depends on the motivations and goals of the program. It also depends on where the money will come from—whether from cutting other programs or from additional sources of revenue—and the impacts of these funding choices reach far beyond the program itself.