Chapter 3

Fusion Research

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History of Fusion Research

RESEARCH BEGINNINGS

Fusion research draws on two independent branches of physics–nuclear physics and plasma physics. Studying the fusion reaction itself is the domain of *nuclear physics.* Studying the behavior of matter under conditions necessary for fusion reactions to take place is the focus of *plasma physics.*

Nuclear Physics

Early in this century, the search for the causes of radioactivity revealed that vast amounts of energy were stored in an atom's nucleus. As early as 1920, this energy was hypothesized to be the heat source that powered the sun and other stars. With the discovery of the neutron in 1932 these nuclear processes began to be understood, and by the time efforts to control fusion reactions in the laboratory began in the 195os, the nuclear physics underlying laboratory fusion reactions were well known. "Then, as now, " noted a recent National Academy of Sciences panel reviewing physics research, "the obstacles to achieving controlled fusion lay not in our ignorance of nuclear physics, but of plasma physics. "[2]

Plasma Physics

Plasma physics, according to the same National Academy review panel, is "the only major branch of physics to come largely into being in the past generation."[3] Its development drew upon a number of previously distinct and independent disciplines, pulling them together into a unified methodology for the study of the plasma state.

Explaining plasmas could not begin until the discovery of the electron in 1895 and the development of the atomic theory of matter. Between 1930 and 1950, the foundations of plasma physics were laid, largely as a byproduct of investigations on topics such as the earth's outer atmosphere, the sun, and various astrophysical phenomena. The advent of space exploration and controlled fusion research–the two major experimental arenas for modern plasma physics—firmly established the field.

Early Fusion Research

The first probe into harnessing fusion power took place during the Manhattan Project, the effort during World War II dedicated to developing an atomic bomb. Some physicists working on the Manhattan Project in Los Alamos, New Mexico, began to consider whether the fusion process could be utilized in nuclear weapons. Such investigations were not a high priority during the war, however, because the national effort was focused on developing weapons that utilized the more immediately promising fission process.

In1949, largely in response to the first Soviet nuclear detonation, senior U.S. scientists and policymakers conducted an extensive, classified (secret) debate about whether hydrogen bombs—weapons that use the fusion process instead of the fission process—could and should be developed. In 19s0, the debate ended when president Truman approved a crash program to build such

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[1] Most of the historical **material in this chapter is based on** *Fusion: Science, Politics, and the Invention of a New Energy Source* (Cambridge, MA: MIT Press, 1982), a comprehensive and extensively documented history of the U.S. fusion program written by Joan Lisa Bromberg under contract with the U.S. Department of Energy. The book is restricted almost entirely to magnetic confinement fusion and covers a period ending in 1978. While Bromberg was given access to unclassified and declassified DOE and national laboratory records, the book does not represent the official position of DOE.

A more popularized history of the fusion program, covering inertial fusion as well as magnetic fusion and extending until 1983, is found in T.A. Heppenheimer, *The Man-Made Sun: The Quest for Fusion Power* **(Boston, MA: Little, Brown & Co., 1984),**

[2] National **Research Council, Panel on the Physics of Plasmas and Fluids, Physics** Survey Committee, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), p. 4.

[3] Ibid., p. 6.

a weapon. The United States detonated its first H-bomb in 1952.[4]

In the beginning, most research in thermonuclear fusion was weapons-related and classified. This research fell under the constraints of the Atomic Energy Act of 1954, which mandated that data concerning the “design, manufacture, or utilization of atomic weapons, ” as well as “the production of special nuclear material” and the “use of special nuclear material in the production of energy,” remain classified indefinitely unless specific action was taken to declassify its

Over the years, some of the emphasis in fusion research shifted from weapons to reactors. Fusion reactors were sought not only to produce “special nuclear **materials”—tritium and plutonium**—needed for nuclear weapons, but also to produce electricity. At the time, both energy production and materials production fell under the restrictions of the Atomic Energy Act that mandated continued classification.

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[4] Herbert York, “The Debate Over the Hydrogen Bomb, ” *Scientific American,* October 1975. There are many names for bombs that use the fusion process: hydrogen bombs, H-bombs, and thermonuclear or hydrogen weapons. Such weapons can have many times the explosive power of fission weapons.

“'Special nuclear material,” as defined in the Atomic Energy Act of 1954, is material capable of undergoing nuclear explosions.

THE U.S. FUSION PROGRAM THROUGH THE DECADES

The nature of the U.S. fusion research program through each decade from its conception to the present is summarized below. The funding profile for U.S. fusion research, both in constant and current dollars, is shown in figures 3-1 and 3-2. Data for these figures is provided in appendix C; for more information on funding for magnetic fusion research, see chapter 6.

The U.S. Atomic Energy Commission (AEC) was responsible for magnetic fusion research from 1951, when the program was formally undertaken, until 1974, when the AEC was disbanded and replaced by the Energy Research and Development Administration (ERDA). In 1977, ERDA in turn was disbanded and its responsibilities transferred to the new Department of Energy (DOE). Since 1977, DOE has managed the magnetic fusion research program.

The 1950s: Era of Optimism and Disillusionment

Project Sherwood

From 1951 until 1958, fusion research was classified; during these years, the program was conducted under the code name “Project Sherwood.” At the outset of Project Sherwood, both field scientists and program managers at the AEC believed that fusion could yield an important technology to supply future electricity needs. In pursuing fusion, scientists and AEC commissioners sought to maintain U.S. scientific supremacy; there could be significant political and economic advantage should fusion lead to a commercially competitive new energy technology. Fusion research would also support the U.S. weapons program. The potential use of fusion reactors for generating weapons materials, as well as the possibility of other military applications, was important to the AEC; thus, during the early 1950s, fusion research grew along with military atomic research.

project Sherwood began optimistically in 1951. At that time, it was estimated that spending about $1 million over a period of 3 to 4 years would be sufficient to learn whether a high-temperature plasma could be confined by a magnetic field. About that amount was budgeted for fusion research from 1951 to 1953. However, the problem proved harder than originally anticipated, and in 1953 the fusion research program expanded. The personnel level increased from 8 in 1952 to 110 in 1955 and rose to over 200 people in 1956. Annual budgets increased from under $1 million to $7 million over the same period.[6]

The United States established several fusion research centers. Federally funded efforts were con-

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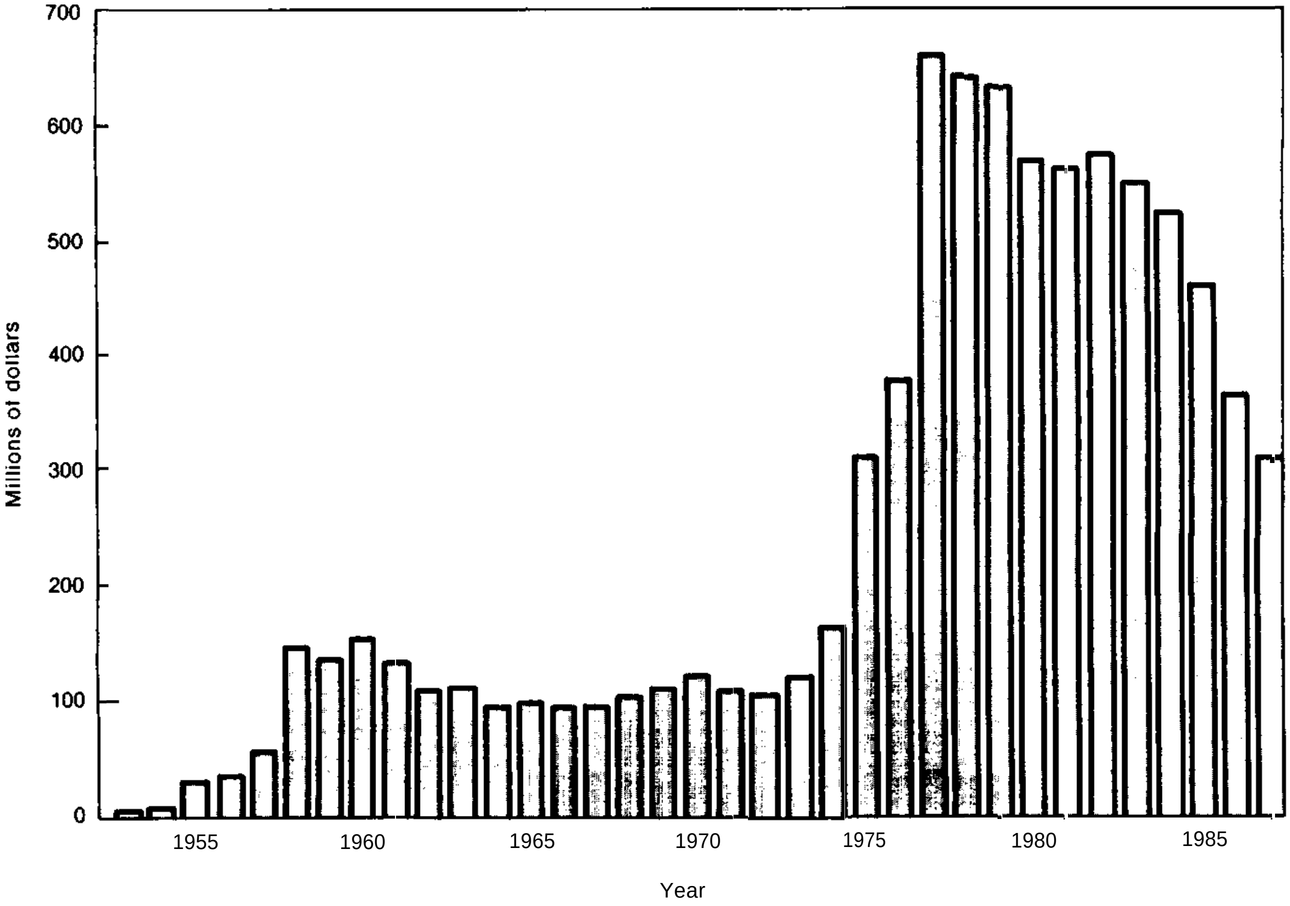
[6] Bromberg, *Fusion,* op. cit., p. 30.

Figure 3-1.—Historical Magnetic Fusion R&D Funding, 1951-87 (in 1988 dollars)



SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986.

ducted at Oak Ridge National Laboratory in Tennessee, Los Alamos Scientific Laboratory in New Mexico, Lawrence Livermore Laboratory in California, and a number of universities, including a major plasma physics laboratory at Princeton University in New Jersey established primarily to conduct fusion research. Private or corporate-sponsored research began in 1956 at the General Electric Co. (GE) in New York and at the newly created General Atomic Corp. in California. Several other companies dedicated a few staff members to monitor the field.

Many different confinement schemes were explored during the early 1950s. Although proponents of the various schemes were careful to note that practical applications lay at least 10 or 20 years in the future, the devices under study were thought to be capable of leading, in a straightforward process of extrapolation, to a commercial reactor. One report concluded in 1958:

> With ingenuity, hard work, and a sprinkling of good luck, it even seems reasonable to hope that a full-scale power-producing thermonuclear device may be built within the next decade or two.[7]

In reality, very little was known about the behavior of matter under the conditions being studied, much less under reactor-like conditions. Experiments were trial-and-error operations, and each one charted new ground. Results were often

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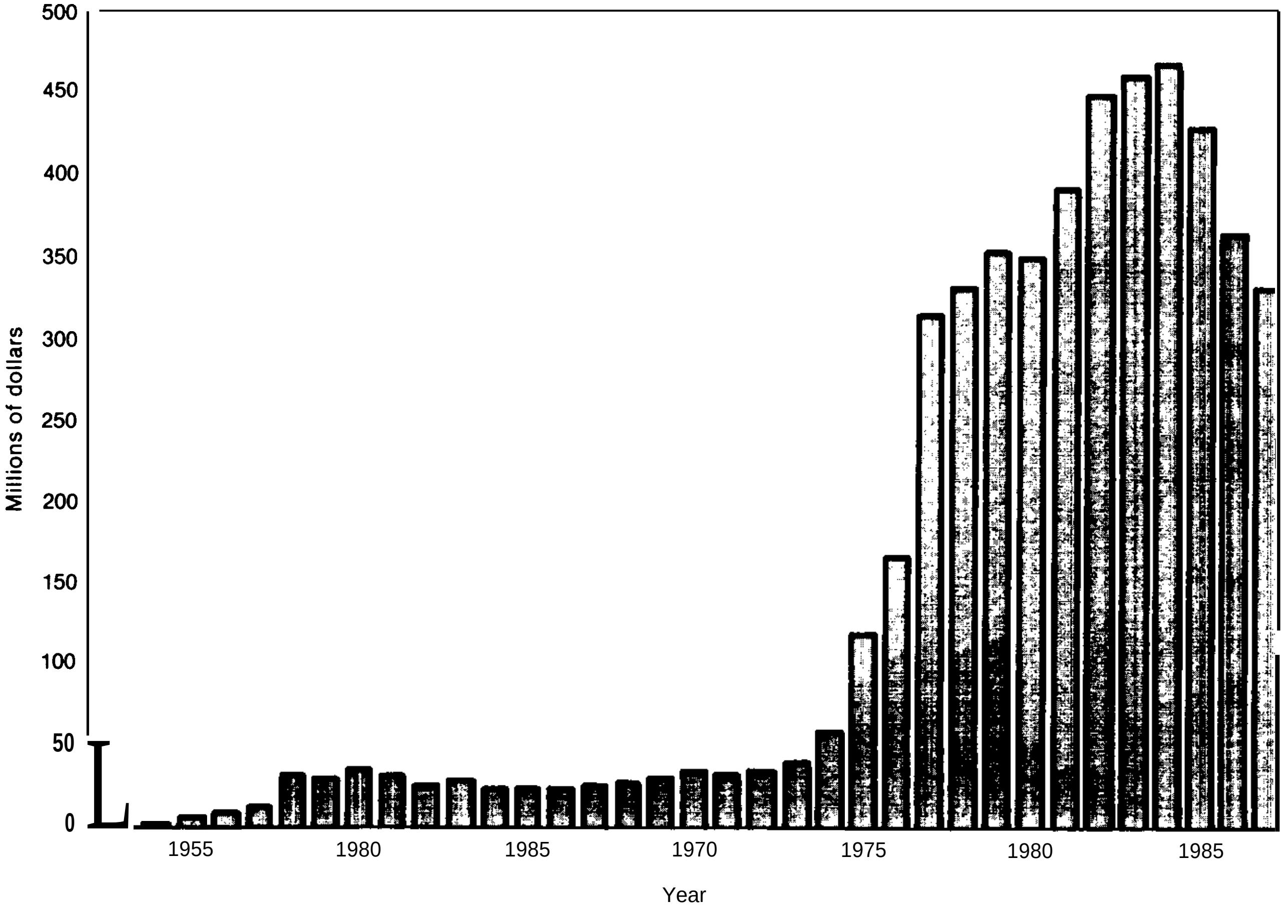
[7] Amasa S. Bishop, *Project Sherwood." The U.S. Program in Controlled Fusion* (Reading, MA: Addison-Wesley Publishing Co., Inc., 1958), p. 170. Bishop managed the AEC fusion program from 1953 to 1956 and again from 1965 to 1970.

Figure 3-2.—Historical Magnetic Fusion R&D Funding, 1951-87 (in currant dollars)



SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986.

ambiguous or misinterpreted, and the theoretical underpinnings of the research were not well established. All devices investigated showed evidence of *“instabilities,”* or disturbances that grew to the point where the plasma escaped confinement faster than expected. The devices studied in the 1950s could not attain Lawson parameters higher than about 10^{10} second-particles per cubic centimeter, a factor of about 10,000 less than the minimum required to make net fusion power.[8] Temperatures attained were about 100 electron volts, in comparison to the minimum requirement of 10,000 electron volts.[9]

Declassification

By the mid to late 1950s, the advantages of declassifying Project Sherwood were recognized, both within the AEC and among scientists in the field. Some U.S. scientists had sought to delay declassification of fusion research because they were optimistic about harnessing controlled fusion reactions in the near future, and they rea-

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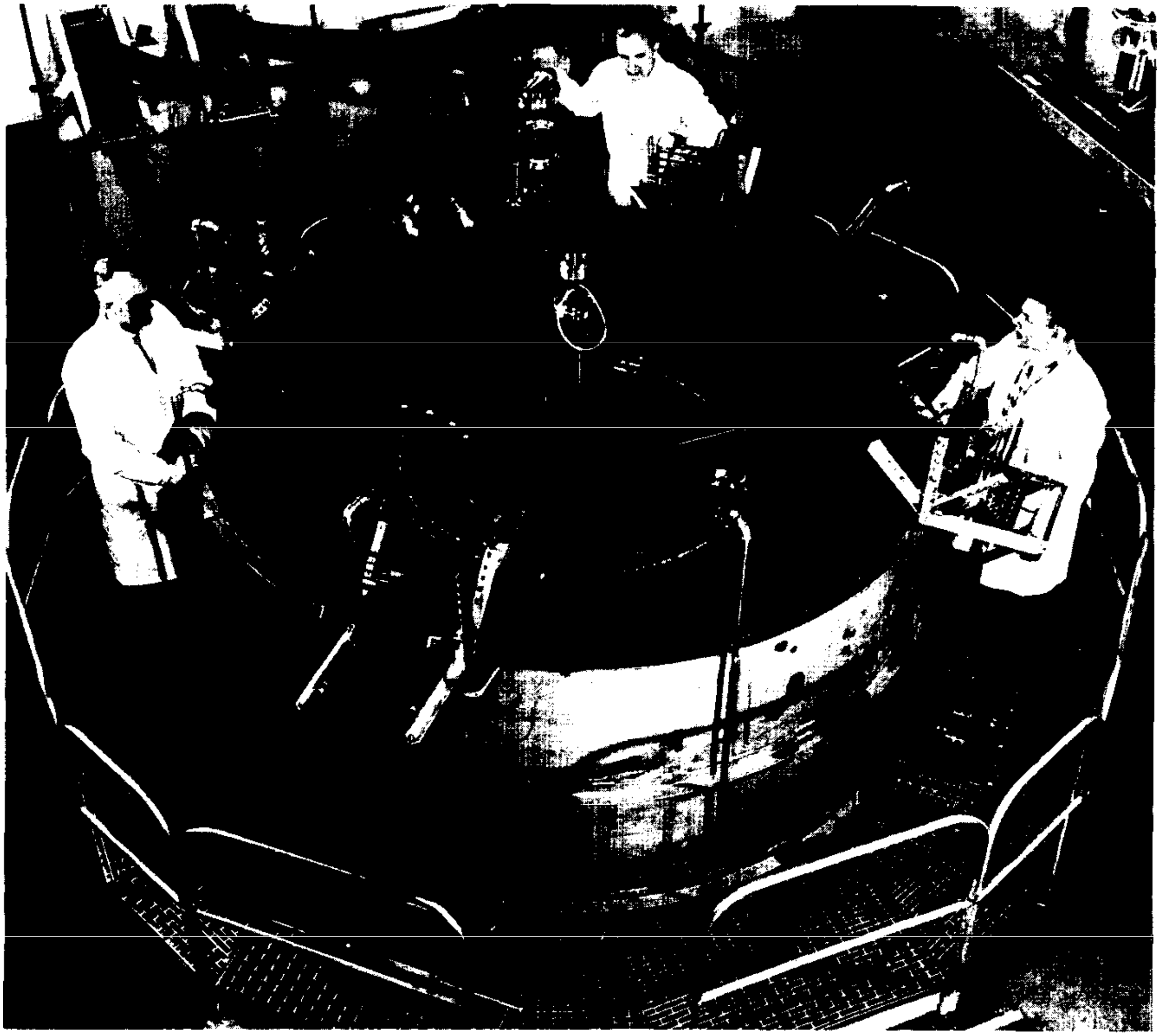
[8] The Lawson parameter is the product of density and confinement time (see ch. 2, note 4). The units in which the Lawson parameter is expressed represent a density (particles per cubic centimeter) multiplied by a time (seconds), and have no immediate physical significance. A product of 3 X 10^{14} second-particles per cubic centimeter is considered the minimum for ignition in a D-T reaction. (See discussion of “energy gain” in ch. 4, pp. 67-68.)

[9] An electron volt is a unit of energy. It is also used as a measure of temperature, representing that temperature at which the average energy of plasma particles is roughly 1 electron volt. (See ch. 2, note 3.)



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sense to classify fusion research, whose application in producing weapons material was still hypothetical, after fission technology that was actually being used for that purpose was declassified.11

U.S. magnetic fusion research was declassified in 1958 at the Second Geneva Conference on the Peaceful Uses of Atomic Energy. Following declassification, it was apparent that the American, British, and Soviet programs were at more or less the same level and were pursuing similar approaches toward confining plasmas. Declassification opened the door to widespread international cooperation in fusion.

The 1960s: A Plateau

Fusion research in the United States proceeded at a steady pace throughout the 1960s. The theoretical framework advanced, but discrepancies between theoretical predictions and experimental results were common. By the mid-1960s, Congress became impatient. **In the late 1950s, mem**bers of Congress had believed that the Federal program would beat the reactor prototype level in 5 or *6* years. Since that time, fusion researchers realized that they had seriously underestimated the complexity of the problem. Therefore, the researchers concentrated on studying plasma behavior rather than on building reactor prototypes. Congress, however, worried that the researchers were building an array of different experiments that did not appear to be leading to an attractive reactor.[12] Thus, in 1963, the House Appropriations Committee recommended a 16 percent cut in the program's operating budget. Much of the cut was restored, but the program ended up with a budget of 7 percent less than requested.

Enthusiasm for the fusion program cooled outside of Congress as well. While remaining supportive of fusion, AEC commissioners were more interested in expanding the fission breeder reactor program .13 GE reviewed its corporate involvement in fusion in 1965 and concluded that "the likelihood of an economically successful fusion electricity station being developed in the foreseeable future is small."[14] GE proposed that the AEC finance its research through a joint effort, but the AEC refused and GE phased out its fusion program. While GE was reconsidering its fusion program, the consortium of Texas utilities that funded fusion research at General Atomic in California withdrew its support.[15] The AEC responded to this decision by funding much of General Atomic's fusion research itself in order to preserve the expertise assembled there. In effect, this response created an additional national laboratory.

In 1965, a prestigious outside review committee evaluated the fusion program. The committee found that the magnetic fusion program had made significant progress, that the United States needed to support research in order to develop the technology, and that the program produced "spin-off" technologies that could benefit the economy. Moreover, the committee stated that the United States would suffer a great loss of international stature if another country demonstrated the feasibility of fusion first. The committee recommended that the fusion budget increase by 15 percent annually and that a new generation of experiments be funded to replace obsolete ones.[16] After considerable deliberation within the AEC and the Bureau of the Budget, an increase in funding was recommended, though not of the magnitude suggested by the committee.

The Tokamak

By 1968, the highest temperatures that had been achieved in a magnetic confinement fusion device were only about 100 electron volts–not appreciably higher than they were in the 1950s. The quality of confinement, as measured by the Lawson parameter, had increased by an order of magnitude (factor of 10) to about 10^{11} second-particles per cubic centimeter. In 1968, however, Soviet scientists announced that they had exceeded the previous best values of each of these parameters by an additional order of magnitude.

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[11] Ibid., pp. 69, 72-73.

[12] Ibid., **pp. 118-119.**

[13] Ibid., p. 136.

[14] Ibid., p. 137.

[15] This consortium has continued to fund a modest level of fusion research at the University of Texas.

[16] Bromberg, *Fusion,* op. cit., pp. 138-139.

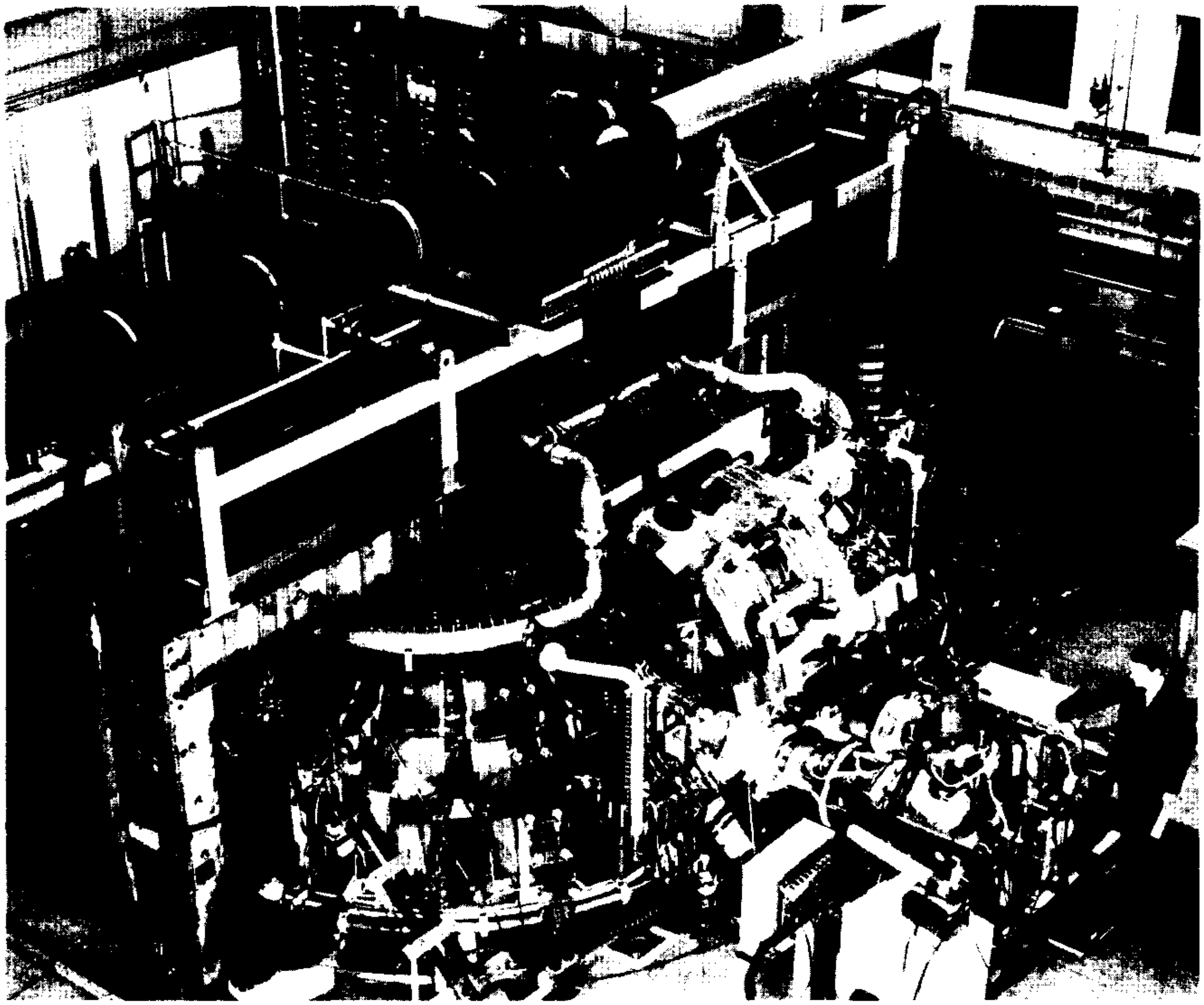

Photo credit: Princeton Plasma Physics Laboratory

Model C Stellarator at Princeton Plasma Physics Laboratory. Designed and built in the late 1950s, the Model C was converted into the United States' first tokamak in 1970.

Using a device named the *"tokamak,"* a Russian acronym taken from the words for "toroidal chamber with magnetic coil," the Soviets claimed to have generated ion temperatures of 500 electron volts, electron temperatures of twice that, and a Lawson parameter of 10^{12} second-particles per cubic centimeter.

The Soviet announcement both excited and troubled the U.S. fusion community. U.S. program administrators worried that the Soviet Union would beat the United States to demonstrating fusion's feasibility. Some U.S. scientists submitted proposals to build tokamaks in the United States, while others argued that previous plans to upgrade existing devices were more important. Many scientists were skeptical of Soviet data, contending that it was ambiguous and not sufficiently compelling to change the emphasis of the U.S. program.

Early in 1969, the director of the Soviet fusion effort invited a British team of scientists to bring its own diagnostic equipment to Moscow to verify

Soviet research results. During the summer of 1969, the British team in Moscow announced its preliminary findings: the Soviet results were genuine, and, in fact, the tokamak performed even better than the Soviets had claimed. This announcement came shortly after the American scientific community had decided to convert the premier Princeton machine, the Model C stellarator, into a tokamak. In addition, funds had been allocated for the development of another tokamak at Oak Ridge National Laboratory. After publication of the British findings, the U.S. program launched three more experimental tokamaks.

The 1970s: Rapid Growth

With the identification of the tokamak as the confinement concept most likely to reach reactor-level conditions, the U.S. fusion program grew rapidly. Between 1972 and 1979, the fusion program's budget increased more than tenfold. Three forces spurred this growth. First, uncertainty over long-range energy supply mobilized public concern for finding new energy technologies. Second, fusion energy, with its potentially inexhaustible fuel supply, looked especially attractive. Third, the growth of the environmental movement and increasing opposition to nuclear fission technology drew public attention to fusion as an energy technology that might prove more environmentally acceptable. The fusion program capitalized on this public support; program leadership placed a very high priority on developing a research plan that could lead to a demonstration reactor.

From Research to Development?

The emphasis on building a demonstration reactor dramatically changed the fusion program. Previous fusion program plans had called for "breakeven-equivalent" to be demonstrated in a device containing only deuterium, to avoid the complications introduced by use of tritium.[17] The new plans called for an experiment fueled with deuterium and tritium (D-T), which would reach breakeven by actually generating fusion power.

During much of the 1970s, the director of the fusion program was largely responsible for reorienting the program toward the use of tritium in an experimental device. He sought to attain breakeven with tritium for a number of reasons:[18]

- **Physics.** The energy released in actual fusion reactions involving tritium introduced a new complication in device operation that could significantly affect experimental behavior. The director thought it was essential to study the physical consequences of releasing fusion energy in a plasma.
- **Psychology.** He also believed that too many fusion scientists were interested in plasma physics as a research enterprise, not as an energy technology. Burning D-T, he thought, would force them to come to grips with the realities of fusion power instead of the abstractions of plasma physics.
- **Engineering.** A D-T experiment would increase the amount of attention given to the engineering aspects of a fusion reactor, departing from the near-total emphasis on plasma physics in fusion research to date.
- **Politics.** A D-T experiment would generate actual fusion power for the first time. This demonstration would dramatize to the public the capabilities of fusion in a more direct way than simply achieving "breakeven-equivalent" conditions.[19] Moreover, this demonstration had to take place soon enough so that the fission breeder reactor would not become established as the long-run energy option of choice.

Many members of the fusion community opposed a D-T machine. They questioned whether the scientific principles underlying tokamak operation were sufficiently known to take such a major step. Moreover, many felt that it was not necessary to construct an experiment at this point in the research program that would involve radioactivity and thus more complications and more expense.

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[17] Tritium is radioactive and difficult to work with. More significantly, its use in fusion experiments generates neutrons that make materials in the device radioactive.

[18] Bromberg, *Fusion,* op. cit., pp. 204-205.

[19] "Breakeven-equivalent" is the attainment of plasma conditions in a deuterium-only plasma equivalent to those that, in a D-T plasma, would produce breakeven. Breakeven-equivalent does not require use of radioactive tritium and does not produce the neutron radiation generated in a breakeven D-T plasma.

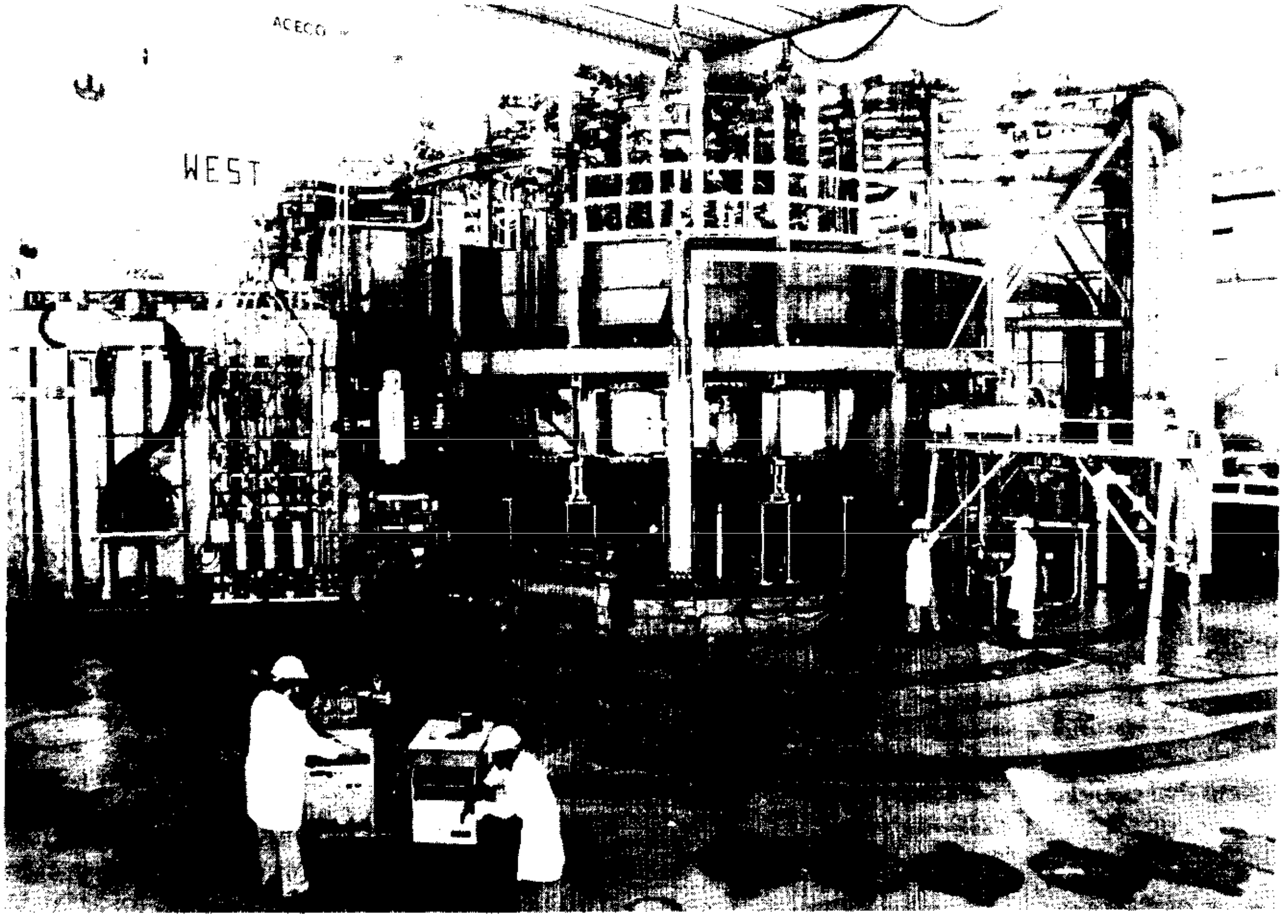

Photo credit: Princeton Plasma Physics Laboratory

The Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory.

In mid-1 973, senior fusion researchers, fusion program managers, and outside observers evaluated the plans to accelerate building a D-T machine. They concluded: 1) that scientific questions should be answered in deuterium experiments, which would be simpler and cheaper to build than machines using tritium, but 2) that a tritium-burning experiment should be conducted on an accelerated schedule.

During this period, congressional and public concern about energy supply was increasing, and, in June 1973, president Nixon announced his intention to nearly double the budget proposed for energy research over the next 5 years. By June 1974, the funding increases necessary to pursue accelerated development of fusion were appropriated. Planning began for a D-T burning breakeven experiment, the Tokamak Fusion Test Reactor (TFTR), to be constructed at the Princeton Plasma Physics Laboratory.

program organization also changed when Congress abolished the AEC in 1974 and transferred its energy research programs to the Energy Research and Development Administration. ERDA was a new agency with a broad mission in energy research. It assumed management of AEC's nuclear fission and fusion programs, as well as programs in solar and renewable technologies, fossil fuels, and conservation.

Concept Competition

The expansion of the tokamak program increased competition for funds among proponents of alternate confinement concepts. Most fusion community leaders believed that the fusion program could not command the budget required to construct more than one additional TFTR-class experiment. Thus, there was some concern about the role of the three remaining major fusion laboratories. Oak Ridge National Laboratory, which had competed unsuccessfully with Princeton to construct the tokamak breakeven experiment, had tokamak experience that would be needed to support the Princeton experiment. The future was more uncertain for the non-tokamak research programs at Los Alamos and Lawrence Livermore national laboratories.

Between the major concepts investigated at these two labs, the "magnetic mirror" at Livermore was selected over the "theta pinch" at Los Alamos to become the principal alternative to the tokamak. Livermore had constructed a series of mirror devices during the 1960s and 1970s, and, in 1976, its proposal to build a greatly scaled-up Mirror Fusion Test Facility (MFTF) was approved. After design and construction of MFTF were underway, researchers developed a design innovation that could improve the performance of the mirror concept. This idea was tested by building the Tandem Mirror Experiment (TMX) and found to be valid. Even so, the improvement was too small to justify changing the MFTF design, so construction proceeded as originally planned.

Livermore scientists then proposed another innovation that seemed to have the potential to make a mirror reactor a viable competitor to a tokamak reactor. This time, the gain appeared to be sufficiently great to warrant modifying the MFTF design, more than tripling its size. Moreover, Livermore scientists had so much confidence in the theory that they proposed to start modifications to MFTF before testing the new concept experimentally. In 1979, they proposed to modify both TMX and MFTF in parallel, with the smaller TMX-Upgrade (TMX-U) to be completed and operated to verify the new concept at a time when substantial work still remained to be done on the revised MFTF (now called MFTF-B). In this way, any changes found to be necessary as a result of tests on TMX-U could be incorporated directly into MFTF-B during its construction. Construction of MFTF-B began in 1981.

Systems Studies

In addition to experiments on confinement concepts, fusion program managers in the 1970s began to consider design attributes of fusion reactors in a systematic way. Scientists and engineers began to address the engineering problems that various confinement methods posed for reactor design, and "reactor relevance" soon became a driving force for additional research. Sustained and serious interest in these design studies, also called systems *studies,* attracted the attention of people outside the fusion community. Several individuals in electric utilities began to follow fusion closely, and the utility research consortium, the Electric Power Research Institute (EPRI), established a Fusion Advisory Committee.

World Effort

During the 1970s, the U.S. fusion program led the world. It had the greatest breadth and depth of confinement concepts under investigation, and its attention to fusion systems and technology was unmatched. However, programs in the Soviet Union, Japan, and Western Europe grew during the 1970s. Each program made plans to build a TFTR-class tokamak to reach breakeven-equivalent conditions: the Joint European Torus (JET) in Europe, JT-60 in Japan, and the T-15 tokamak in the Soviet Union. All of these machines except the T-1 5 are now operational. The international aspects of fusion research are discussed more fully in chapter 7.

Program Reorientation

In 1977, president Carter incorporated the functions of ERDA, including the fusion program, into a new agency, the Department of Energy. DOE reemphasized support for nuclear fission, primarily due to concern over the proliferation aspects of breeder reactors, and it increased support for solar energy, conversion from oil and gas to coal, and conservation.[20]

The first director of the DOE Office of Energy Research believed that the budget for the fusion program was too large for fusion's uncertain prospects. In his capacity as scientific advisor to the

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[20] Bromberg, *Fusion,* op. cit., P. 235.

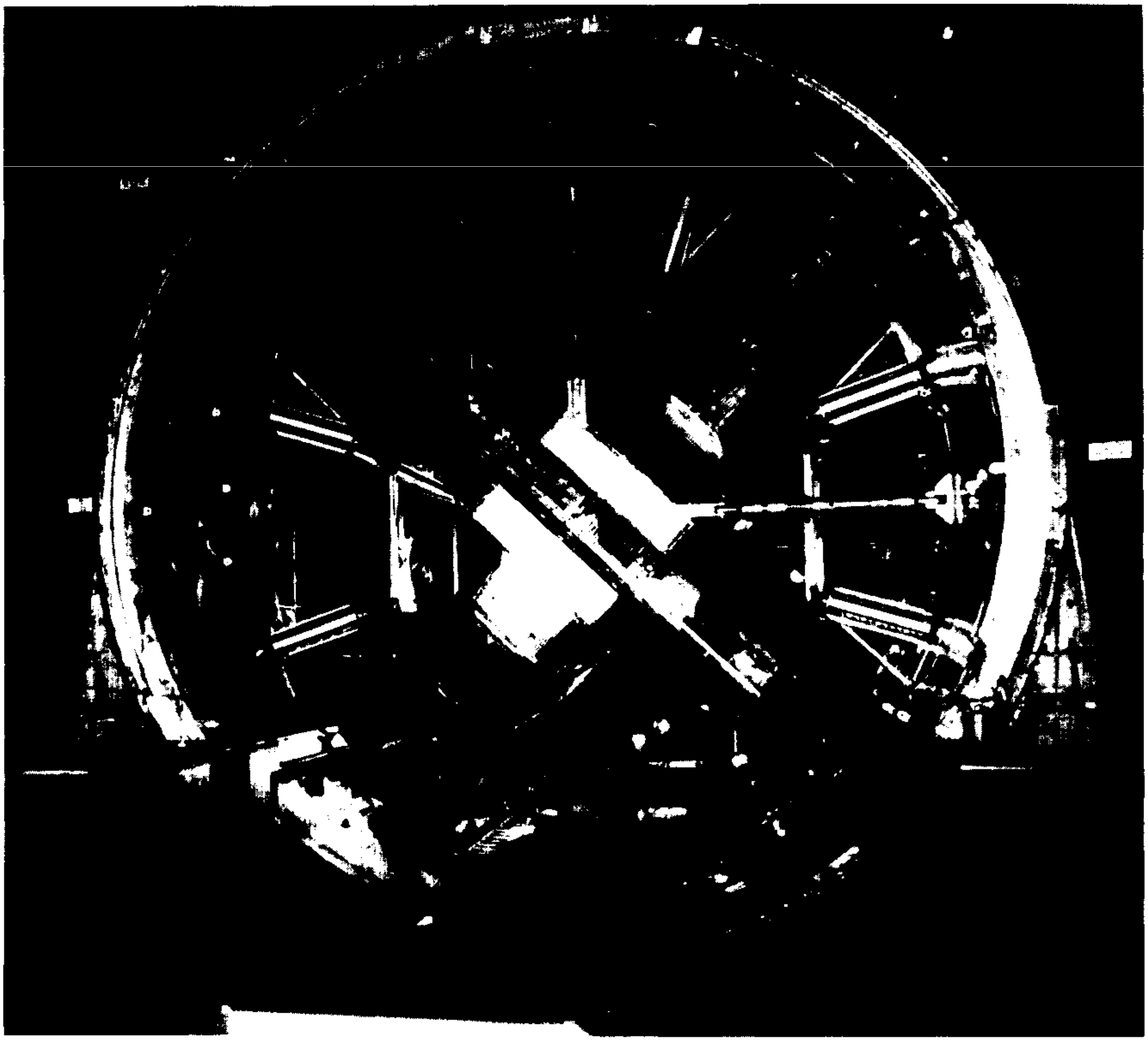

Photo credit: Lawrence Livermore National Laboratory

Installation of one of the end cell magnets for MFTF-B. Another view of this magnet is shown on p. 87.

Secretary of Energy, he commissioned a high-level outside review of the program, a review that he expected would recommend cutting the budget and relaxing the program's emphasis on an early demonstration reactor.[21] On the contrary, the review panel praised the management and scientific achievements of the fusion program and did not recommend budget cuts. Mostly as a result of the panel's findings, the Secretary of Energy subsequently reaffirmed the near-term planning of the fusion program. With few modifications, DOE management supported maintaining current budget levels, pushing towards early completion and operation of TFTR, maintaining ongoing fusion system studies, and accelerating fusion technology development.

Although the short-term fusion program plans continued much as before, the long-term strat-

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Z' Ibid., p. 236.

egy under DOE in the late 1970s differed from the ERDA strategy earlier in the decade. The review panel stated in its report that "the first objective of the program must be to determine the highest potential of fusion as a practical source of energy." This meant not proceeding with construction of a tokamak device to succeed TFTR until "a convincing case should be made that Tokamaks can be engineered into attractive energy producers."[22] In effect, the committee recommended that the tokamak program be held up at the TFTR stage until other devices, such as the mirror, could be compared to it at relatively equivalent stages of development.

Under DOE, the fusion program did not have the sense of urgency that was so important earlier in the decade. Fusion could not mitigate the short-term oil and gas crisis facing the United States. Furthermore, as a potentially inexhaustible long-range energy source (along with solar energy and the fission breeder reactor), fusion was not thought needed until well into the next century. Therefore, there appeared to be no compelling reasons to develop a fusion demonstration plant rapidly .23

The 1980s: Leveling Off

The fusion program has continued to make substantial technical progress during the 1980s. Several world machines have the potential to achieve breakeven, or breakeven-equivalent conditions, within the decade; in addition, significant advances in plasma physics and fusion technology continue.[24]

ERAB Review of the Fusion Program, 1980

In 1980, the Energy Research Advisory Board (ERAB), a standing committee that advises the Secretary of Energy, established a committee to review DOE's fusion program. The committee's report evaluated technical progress in the fusion program over the previous few years and found many accomplishments that justified the panel's confidence that breakeven was near. The panel concluded that:

> . . . the United States is now ready to embark on the next step toward the goal of achieving economic fusion power: Exploration of the engineering feasibility of fusion .25

The panel proposed that the program begin planning a Fusion Engineering Device (FED), which would provide a focus for development of reactor-relevant technologies and components, enable researchers to evaluate safety issues associated with fusion power, and facilitate investigation of additional plasma physics issues. This device would be built and operated as part of a broad program of engineering experimentation and analysis to be conducted by a new fusion engineering center. The ERAB panel recognized that planning and constructing FED would require a doubling of the fusion budget over the next 5 to 7 years, and it recommended this budget increase.

The Magnetic Fusion Energy Engineering Act, 1980

Many of the recommendations of the ERAB panel were incorporated into the Magnetic Fusion Energy Engineering Act (MFEE Act), passed by Congress in September 1980.[26] Passage of the MFEE Act was largely a result of Representative Mike McCormack's (D-Washington) efforts. It urged acceleration of the national effort in magnetic fusion research, development, and demonstration activities. Like the ERAB report, the act recommended creation of a Magnetic Fusion Engineering Center to coordinate major magnetic fusion engineering devices.

The MFEE Act recommended that funding levels for magnetic fusion be doubled (in constant dollars) within 7 years. However, it did not ap-

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[22] Foster Committee, Final Report (DOE/ER-0008, June 1978). Quoted in T.A. Heppenheimer, *The Man-Made Sun,* op. cit., pp. 201-202.

[23] Bromberg, Fusion, op. cit., p. 247.

[24] Many of the technical accomplishments in the fusion program and the tasks still to be done are discussed in ch. *4* of this assessment.

[25] "Report on the Department of Energy's Magnetic Fusion Program," prepared by the Fusion Review Panel of the Energy Research Advisory Board, August 1980, as quoted in *Fusion Energy: An Overview of the Magnetic Confinement Approach, Its Objectives, and Pace,* a report prepared for the Subcommittee on Energy Research and Production, House Committee on Science and Technology, 96th Cong., 2d sess., Serial GGG, December 1980, p. 133.

[26] Public Law 96-386, signed into law on Oct. 7, 1980.

propriate these increases, and there was no follow-up. in effect, the act indicated that Congress considered the fusion program worthwhile and deserving of support but was unable or unwilling to make a long-term commitment to substantially increase expenditures. Actual appropriations in the 1980s did not grow at the level specified in the act and in fact continued the drop in constant dollar funding that began in 1977.

Reagan Administration Budgets and Philosophy

Energy R&D budgets underwent radical cuts in 1981 at the beginning of the Reagan Administration. The Reagan Administration stated that development activity belonged in the private sector and that the government could encourage this activity most effectively by staying out of it. Accordingly, DOE research budgets for solar energy, fossil fuel technology, fission technology, and energy conservation—those energy areas most heavily weighted towards development or demonstration, as opposed to research—were substantially reduced. In contrast, the Reagan Administration continued to support government funding for long-term, high-risk programs–e.g., fusion research–that would not attract private investment. Therefore, although the fusion research budget has decreased in the 1980s, it has not been cut as severely as some of DOE's other energy R&D programs.

With annual budget appropriations falling, the ambitious plans of the 1970s, which culminated in the MFEE Act of 1980, could not be implemented. Thus, the fusion program has had to modify its program strategy; subsequent plans attempted to identify the most important aspects of the fusion program to pursue.

The Comprehensive Program Management Plan, 1983

The MFEE Act required that the Secretary of Energy prepare a Comprehensive Program Management Plan (CPMP) outlining the fusion program's strategy and schedule. This plan was completed by DOE and transmitted to Congress in 1983.[27] The CPMP attempted to satisfy the emphases of the MFEE Act within the fiscal constraints imposed by the Reagan Administration. The plan also sought to preserve the role of international leadership in fusion for the United States.

The CPMP had a clear reactor emphasis, but it was also consistent with Reagan Administration philosophy towards development. The plan explicitly ruled out government construction of a demonstration reactor, stating that:

> The primary objectives of the [fusion] program are designed to provide a technical basis for decisions by the private sector on whether to proceed with the commercial development of fusion energy. Proceeding with a Federally funded demonstration plant is not part of this plan .[28]

The CPMP stated that within the next decade, the fusion program would select a plasma confinement concept to undergo further development as a power reactor core. The plan defined two stages that would permit a decision to be made to build a demonstration reactor by the year 2000.

ERAB Review of the Fusion Program, 1983

An additional provision of the MFEE Act established a technical panel on magnetic fusion as an ERAB subcommittee. The subcommittee was mandated to conduct a triennial review of the fusion program, with the first such review to be conducted in 1983.

The subcommittee's report[29] recognized that budgetary constraints had made it impossible to accomplish the goals of the MFEE Act on the timescale envisioned. The panel recommended that DOE abandon the CPMP, stating that it would force the program to make a choice between tan-

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[27] *Comprehensive Program Management Plan (CPMP) for Magnetic Fusion Energy,* June 1983. Submitted to the House Science and Technology Committee by the Secretary of Energy pursuant to the Magnetic Fusion Energy Engineering Act.

[28] Ibid., p. 2.

[29] Energy Research Advisory Board, Magnetic *Fusion Energy Research and Development,* Final Report prepared by the Technical Panel on Magnetic Fusion of the Energy Research Advisory Board, DOE/S-0026, January 1984.

dem mirror and tokamak confinement concepts before constructing another major device, a choice that in turn would require delaying progress on the tokamak. The panel also noted that the CPMP's schedule called for construction of a next-generation engineering test reactor—a major facility intended to explore engineering aspects of fusion –before necessary technology development could be completed.

As a revised program strategy, the ERAB panel recommended that a tokamak follow-up device to TFTR be built to study scientific issues. The panel recommended that the reactor engineering efforts be postponed until additional resources were available, and that a strong and innovative base program be maintained in plasma physics, technology development, and alternative confinement concepts.

The Magnetic Fusion Program Plan, 1985

DOE revised its program plan in response to the criticisms of the ERAB subcommittee. In 1985, DOE issued the Magnetic Fusion Program Plan (MFPP), which stated that "the goal of the magnetic fusion program is to establish the scientific and technological base required for fusion energy. "[30] Unlike the CPMP, however, the MFPP lessened the reactor emphasis, concentrated more on the science and engineering requirements, and relaxed the schedule for fusion development:

> The schedule for completing magnetic fusion development is directly related to the technical, economic, and political uncertainties associated with energy supply, which are likely to exist for several decades. The Magnetic Fusion Program Plan is a strategy for solving fusion's technical problems within a time frame keyed to resolution of other areas of energy development.[31]

Like the CPMP, the MFPP did not extend to construction of a fusion demonstration reactor. The plan laid out key technical issues that must be resolved by the fusion program and set out a goal of international collaboration, rather than international leadership, for the U.S. fusion program.

ERAB Review of the Fusion Program, 1986

The second triennial review of the magnetic fusion program was completed by the ERAB subcommittee on magnetic fusion in November 1986.[32] The subcommittee endorsed the fusion program's direction, strategy, and plan and reaffirmed the need to investigate fusion energy as "an attractive energy source of great potential for the future." The panel specifically considered two issues of great importance to the future direction of the program: 1) the construction of a Compact Ignition Tokamak (CIT) as an experiment that would extend scientific understanding beyond that obtainable in TFTR; and 2) the role of international collaboration in an engineering test reactor project.

The Compact Ignition Tokamak.–Several years of TFTR operation have shown continued progress both in understanding and in achieving confinement. TFTR has attained Lawson parameters above 10^{14} second-particles per cubic centimeter (a factor of 10,000 improvement over 1950's results) and ion temperatures of 20,000 electron volts (a factor of 200 improvement). Attainment of actual breakeven when tritium is introduced seems highly probable, and the fusion community has been actively exploring options for a next step beyond TFTR. This has led to DOE recommendations for CIT construction.

CIT will explore the physics associated with ignited plasmas. The ERAB subcommittee concluded that CIT is "an essential and timely project,"[33] both because it will address a fundamental physics issue and because it will provide technical information and experience valuable to the engineering test reactor. ERAB recommended providing an increment to the magnetic fusion program budget to prevent funding for CIT from being taken from other program areas. The construction cost of CIT, in 1986 dollars, has been esti-

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[30] U.S. Department of Energy, Office of Energy Research, *Magnetic Fusion Program Plan,* DOE/ER-0214, February 1985, Executive Summary.

[31] Ibid.

[32] Energy Research Advisory Board, *Report of the Technical panel on Magnetic Fusion of the Energy Research Advisory Board,* prepared for the U.S. Department of Energy, November 1986.

[33] Ibid., p. 1.

mated at $300 million for the facility, plus about $60 million for diagnostic equipment and associated R&D. This estimate assumes that the facility will be located at Princeton Plasma Physics Laboratory, where, according to DOE, site credits will save about $200 million.[34]

The Role of International Collaboration.–The subcommittee endorsed current DOE efforts in international collaboration. In particular, the panel supported the idea of constructing an international engineering test reactor. As envisioned, this device—called the International Thermonuclear Experimental Reactor (ITER)—will be a large experimental facility designed to explore engineering and technological issues relevant to fusion reactors. The ERAB subcommittee stated that "the United States should consider reaching out to other nations to establish a multinational structure for fusion relationships."[35] However, ERAB also recognized the inherent complexity and uncertainty of major international collaborations, pointing out that "some realistic consideration must be given to the possibility that international collaboration on a large scale may not come about."[36] At present, DOE is investigating the potential of undertaking a joint planning activity with the other major fusion powers on a conceptual design for ITER, along with supporting R&D.

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[34] Ibid., p. 11. Site credits refer to the savings that result from constructing the project at a location that already has some of the needed equipment in place. By constructing CIT at Princeton, the experiment will be able to take advantage of the existing TFTR power supplies and other equipment.

[35] Ibid., p. 14.

[36] Ibid., p. 17. A detailed discussion of international collaboration on ITER and other projects can be found in ch. 7 of this assessment.