Chapter 1

Executive Summary

CONTENTS

Figures

Table

Chapter 1
Executive Summary

OVERVIEW

Potential Role of Fusion

If successfully developed, nuclear fusion could provide humanity with an effectively unlimited source of electricity that has environmental and safety advantages over other electric energy technologies. However, it is too early to tell whether these advantages, which could be significant, can be economically realized. **Research aimed at developing fusion as an energy source has been vigorously pursued since the 1950s, and, despite considerable progress in recent years, it appears that at least three decades of additional research arid development will be required before a prototype commercial fusion reactor can be demonstrated.**

The Policy Context

The budget for fusion research increased more than tenfold in the 1970s, due largely to growing public concern about environmental protection and uncertainty in long-range energy supply. However, a much-reduced sense of public urgency in the 1980s, coupled with the mounting Federal budget deficit, halted and then reversed the growth of the fusion budget. Today, the fusion program is being funded (in 1986 dollars) at about half of its peak level of a decade ago (see figures 1-1 and 1-2).

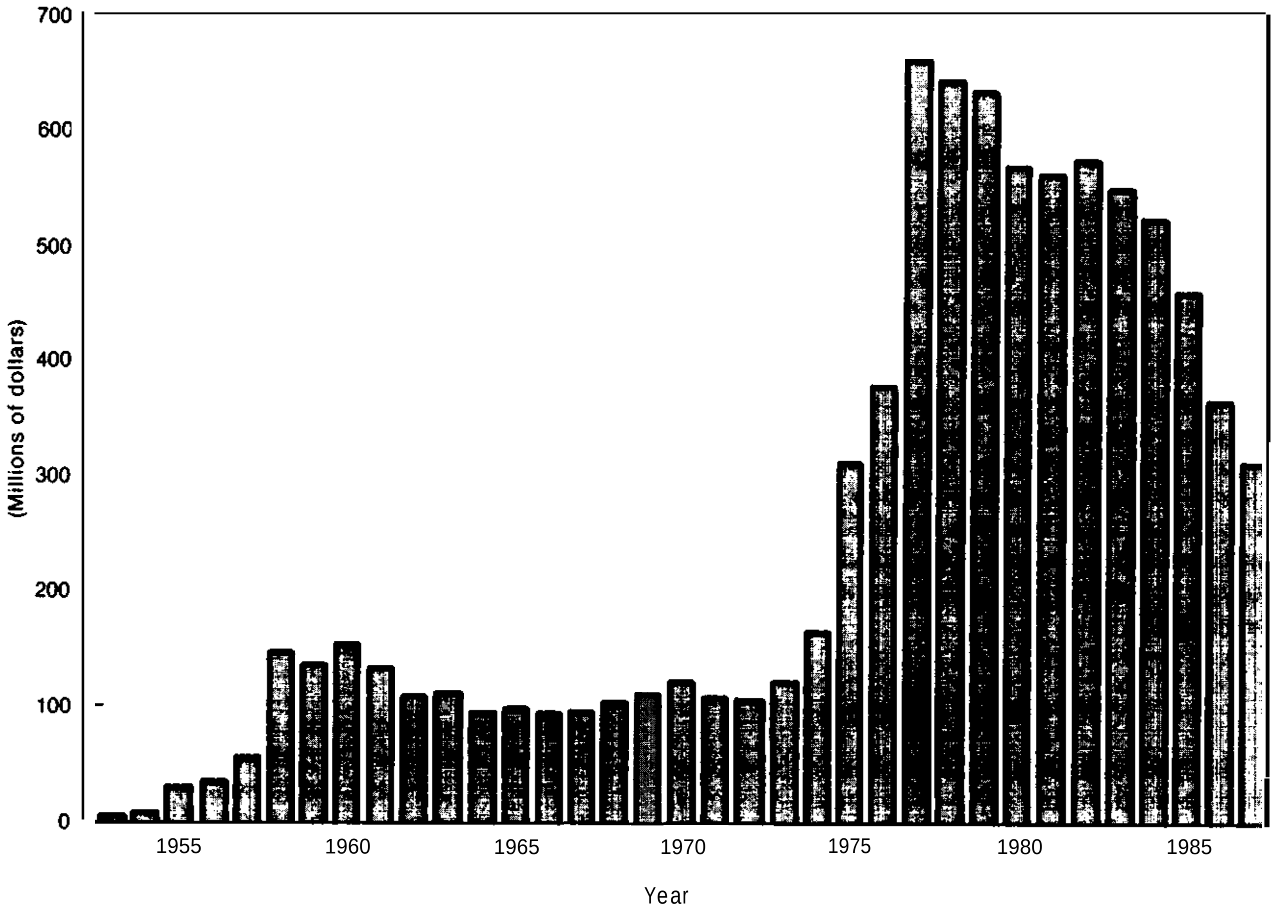
The change in the fusion program's status over the past 10 years has not resulted from poor technical performance or a more pessimistic evaluation of fusion's prospects. On the contrary, the program has made substantial progress. However, the disappearance of a perceived need for near-term commercialization has reduced the impetus to develop commercial fusion energy and has tightened pressure on fusion research budgets. Over the past decade, the fusion program has been unable to maintain a constant funding level, much less command the substantial funding increases required for next-generation facilities. In fact, due to funding constraints, the program has been unable to complete and operate some of its existing facilities.

The Department of Energy (DOE) manages the U.S. fusion program, and its goal is to evaluate fusion's technological feasibility–to determine whether or not a fusion reactor can be designed and built—early in the 21st century. A positive evaluation would enable a decision to be made at that time to construct a prototype commercial reactor. **However, this schedule cannot be met under existing U.S. fusion budgets. The DOE plan requires either that U.S. budgets be increased substantially or that the world fusion programs collaborate much more closely on fusion research.**

Choices made over the next several years can place the U.S. fusion program on one of four fundamentally different paths, which are discussed more thoroughly in chapter 8 of this report:

1. With substantial funding increases, the fusion program could complete its currently mapped-out research effort domestically, permitting decisions to be made early in the next century concerning fusion's potential for commercialization.
2. At only moderate increases in U.S. funding levels, the same results as above might be attainable—although possibly somewhat delayed–if the United States can work with some or all of the world's other major fusion programs (Western Europe, Japan, and the Soviet Union) at an unprecedented level of collaboration.
3. Decreased funding levels, or current funding levels in the absence of extensive collaboration, would require modification of the program's overall goals. At these constrained funding levels, U.S. evaluation of fusion as an energy technology would be delayed.

Figure 1-1.—Historical Magnetic Fusion R&D Funding, 1951087 (in 1986 dollars)



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

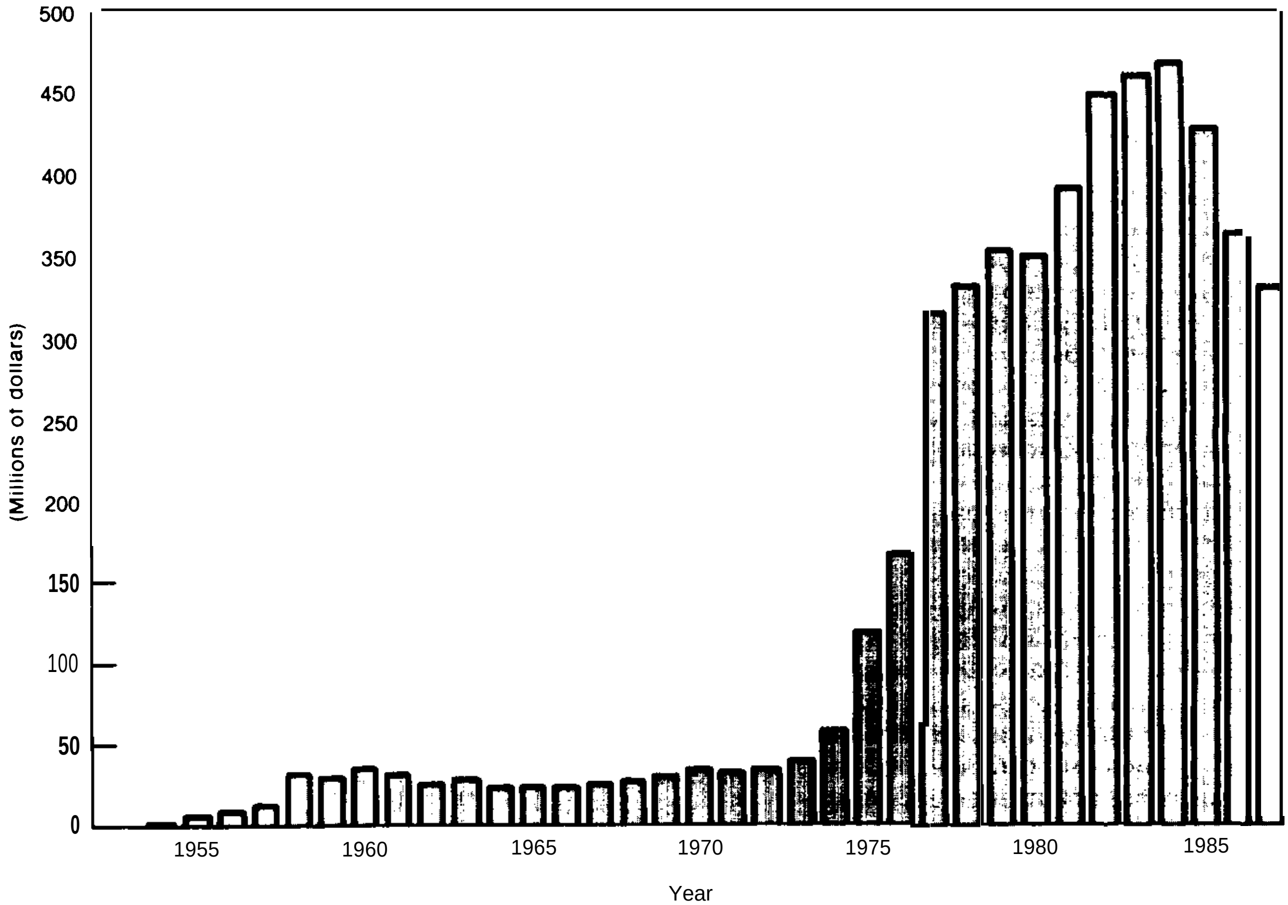
4. If fusion research ceased in the United States, the possibility of domestically developing fusion as an energy technology would be foreclosed unless and until funding were restored. Work would probably continue abroad, although possibly at a reduced pace; resumption of research at a later time in the United States would be possible but difficult.

Findings

Here are some of the overall findings from OTA's analysis:

- Experiments now built or proposed should, over the next few years, resolve most of the major remaining scientific uncertainties regarding the fusion process. If those experiments do not uncover major surprises, it is likely–although by no means certain–that the engineering work necessary to build an electricity-producing fusion reactor can be completed successfully.
- Additional scientific understanding and technological development is required before fusion's potential can be assessed. It will take at least 20 years, under the best circumstances, to determine whether construction of a prototype commercial fusion reactor will be possible or desirable; additional time beyond then will be required to build, operate, and evaluate such a device.
- It is now too early to tell whether fusion reactors, once developed, can be economically competitive with other energy technologies.

Figure 1-2.—Historical Magnetic Fusion R&D Funding, 1951-87 (In current dollars)



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

- Demonstration and commercialization of fusion power will take several decades after completion of the research program. Even under the most favorable circumstances, it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation’s electricity demand before the middle of the 21st century.

- With appropriate design, fusion reactors could be environmentally superior to other nuclear and fossil energy production technologies. Unlike fossil fuel combustion, fusion reactors do not produce carbon dioxide gas, whose accumulation in the atmosphere could affect world climate. Unlike nuclear fission–the process utilized in existing nuclear powerplants—fusion reactors should not produce high-level, long-lived radioactive wastes.
- One of the most attractive features of fusion is its essentially unlimited fuel supply. The only resources possibly constraining fusion’s development might be the materials needed to build fusion reactors. At this stage of development, it is impossible to determine what materials will eventually be developed and selected for fusion reactor construction.
- If fusion technology is developed successfully, it should be possible to design fusion reactors with a higher degree of safety assurance than fission reactors. It may be possible to design fusion reactors that are incapable of causing any immediate off-site fatalities in the event of malfunction, natural disaster, or operator error.

- potential problems with other major sources of electricity—fossil fuels and nuclear fission–provide incentives to develop alternate energy technologies as well as to substantially improve the efficiency of energy use. Fusion is one of several technologies being explored.
- It is unlikely that major, irreversible energy shortages will occur early in the next century that could only be ameliorated by the crash development of fusion power. There is little to be gained—and a great deal to be lost–by introducing fusion before its potential economic, environmental, and safety capabilities are attained. Even if difficulties with other energy technologies are encountered that call for the urgent development of an alternative source of energy supply, that alternative must be preferable in order to be accepted. It would be unwise to emphasize one fusion feature—economics or safety or environmental advantages—over the others before we know which aspect will be most important for fusion's eventual acceptance.
- Due to the high risk and the long time before any return can be expected, private industry has not invested appreciably in fusion research and cannot be expected to do so in the near future. But, unless the government decides to own and operate fusion generating stations, the responsibility for fusion research, development, and commercialization must be transferred to private industry at some stage. The nature and timing of this transition are highly controversial.
- 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 do 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 difficult to use them to justify one field of study over another.
- Fusion research has a long history of successful and mutually beneficial international cooperation, If this tradition can be extrapolated in the future to an unprecedented level of collaboration, much of the remaining cost of developing fusion power can be shared among the world's major fusion programs.
- International collaboration cannot substitute for a strong domestic research program. If the domestic program is sacrificed to support international projects, the rationale for collaboration will be lost and the ability to conduct it successfully will be compromised.
- Agreeing to collaborate on fusion research, both within the U.S. Government and between the U.S. Government and potential partners, will require sustained support at the highest levels of government. A variety of potential difficulties associated with large-scale collaborative projects will have to be resolved, and presidential support will be required. If these difficulties can be resolved, the benefits of successful collaboration are substantial.

A QUICK FUSION PRIMER

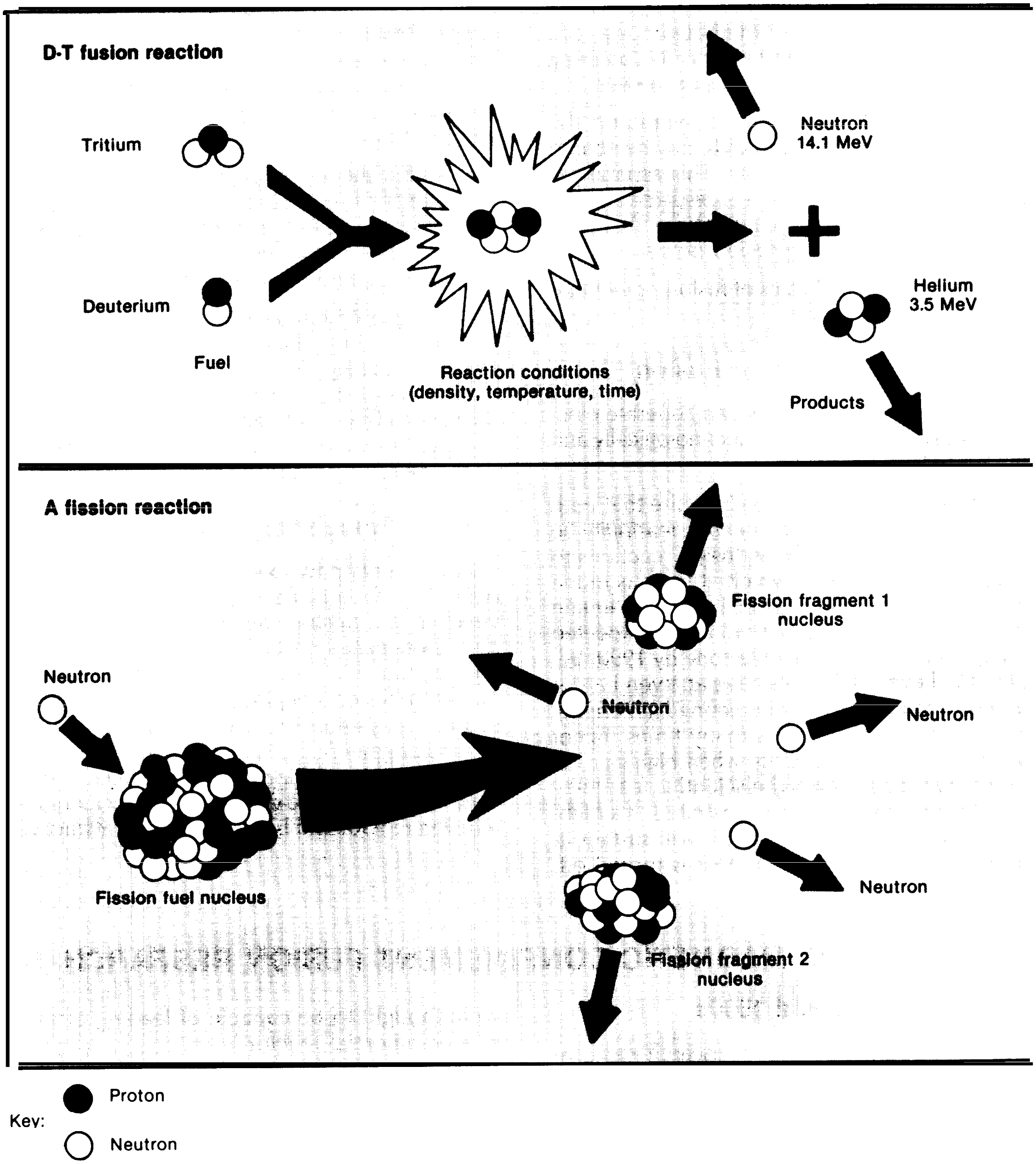
The Fusion Reaction

in a fusion reaction, the nuclei–or central cores—of light atoms combine or fuse together; when they do, energy is released. In a sense, fusion is the opposite of *fission,* the process utilized in existing nuclear powerplants (see figure 1 -3), in which energy is released when a heavy nucleus splits into smaller pieces.

The lightest atom, hydrogen, is the easiest one to use for fusion. Hydrogen has three forms, or isotopes; two of them—deuterium (D) and tritium (T)–in combination work the best in fusion reactions. The kinetic energy released in the D-T reaction can be converted to heat, which in turn can be used to make steam to drive a turbine to generate electricity.

But a fusion reaction cannot happen unless certain conditions are met. To fuse hydrogen nuclei together, the nuclei must be heated to approximately 100 million degrees Celsius (C). At these

Figure 1-3.—The D-T Fusion Reaction and a Fission Reaction



MeV: million electron volts

SOURCE: Adapted from Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 2; Office of Technology Assessment (fission), 1987.

temperatures, matter exists as plasrna, a state in which atoms are broken down into electrons and nuclei. Keeping a plasma hot enough for a long enough period of time, and effectively confining it, are crucial for generating fusion power.

While no solid container can withstand the heat of a plasma, magnetic fields may be able to confine a plasma successfully. This assessment discusses magnetic confinement research and the various magnetic field configurations that look promising for producing fusion power.

More detail on the basics of fusion power can be found in chapter 2.

The Feasibility of Fusion

Before fusion powerplants can generate electricity, fusion must be proven technologically and commercially feasible.

Technological feasibility will require that both scientific *feasibility* and engineering *feasibility* be shown. Scientists must bring fusion reactions to *breakeven,* the point at which at least as much energy is produced as must be input to maintain the reaction. Existing experiments are expected to reach this long-elusive milestone by 1990. Beyond breakeven, scientists have an even harder but more important task of creating high energy gain–energy output that is many times higher than the energy input. Only when high-gain reactions are produced will the scientific feasibility of the fusion process be demonstrated. If a high-gain reaction reaches *ignition,* it will sustain itself even when the external heat is turned off.

Once scientific feasibility of fusion as a potential energy source is established, the engineering development necessary to develop fusion reactors must be completed. Engineering feasibility denotes the successful development of reliable components, systems, and subsystems for operating fusion reactors.

Scientific and engineering feasibility, although involving different issues, are interdependent. Demonstrating either one will require advances to be made in basic scientific understanding as well as in technological capability.

The goal of fusion research is to prove fusion's technological feasibility so that its commercial feasibility is likely. To be marketable, fusion power must be socially and environmentally acceptable and economically attractive compared to its competitors, and it must meet regulatory and licensing requirements.

Probability of Success

Experiments now existing or proposed to be built should be sufficient, within the next few years, to demonstrate fusion's scientific feasibility. If these experiments do not uncover unfavorable surprises, it appears likely–although not certain—that fusion's engineering feasibility can be subsequently established. Most of the technological and engineering challenges to designing and building a reactor have been identified. **However, it cannot yet be determined whether or not a fusion reactor will be commercially attractive.**

HISTORY OF MAGNETIC CONFINEMENT FUSION RESEARCH

1950s and 1960s

From 1951 until 1958, fusion research was conducted by the U.S. Atomic Energy Commission (AEC) in a secret program code-named "Project Sherwood." Many different magnetic confinement concepts were explored during the early 1950s. Although researchers were careful to note that practical applications lay at least 10 to 20 years in the future, the devices being studied were thought to be capable of leading directly to a commercial reactor.

In reality, however, very little was known about the behavior of plasma in experiments and even less about how it would act under the conditions required for fusion reactors. Experimental results were often ambiguous or misinterpreted, and the theoretical understanding underlying the research was not well established. By 1958—as people

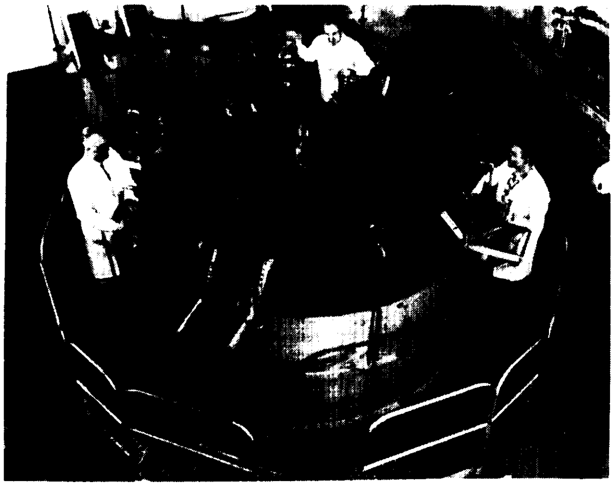


Photo credtt: Los Alamos National Laboratory

Perhapsatron, built and operated in the 1950s at Los Alamos Scientific Laboratory.

realized that harnessing magnetic fusion was going to be difficult and that national security considerations were less immediate—the research was declassified. This action made widespread international cooperation in fusion research possible, particularly since the countries involved realized that the state of their research programs was more or less equivalent.

With the optimism of the **1950s** tempered, fusion researchers in the United States proceeded at a steady pace throughout the 1960s. In 1968, Soviet scientists announced a major breakthrough in plasma confinement in a device called a "tokamak." After verifying Soviet results, the other world fusion programs redirected their efforts toward development of the tokamak.

1970s and 1980s

With the identification of the tokamak as a confinement concept 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. This growth was due in part to uncertainty in the early 1970s concerning long-range energy supply; fusion energy, with its potentially inexhaustible fuel supply, appeared to be an attractive alternative to exhaustible resources such as oil and gas. In addition, the growth of the environmental movement and increasing opposition to nuclear fission technology drew public support to fusion as an energy technology that might prove more environmentally acceptable than other energy technologies.

The fusion program capitalized on this public support; program leadership placed a high priority on developing a research plan that could lead to a demonstration reactor. Planning began for the Tokamak Fusion Test Reactor, a new experiment using D-T fuel that would reach breakeven. By 1974, the funding increases necessary to pursue accelerated development of fusion were appropriated.

Program organization changed twice during the 1970s. In 1974, Congress abolished the AEC and transferred its energy research programs to the newly created Energy Research and Development Administration (ERDA). ERDA assumed management of the AEC's nuclear fission and fusion programs, as well as programs in solar and renewable technologies, fossil fuels, and conservation. Three years later, President Carter incorporated the functions of ERDA into a new agency, the Department of Energy (DOE).

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

Nevertheless, the Magnetic Fusion Energy Engineering Act of 1980 urged acceleration of the national effort in magnetic fusion research, development, and demonstration activities. The act recommended that funding levels for magnetic fusion double (in constant dollars) within 7 years. However, Congress did not appropriate these increases, and there was no follow-up. Actual appropriations in the 1980s have not grown at the levels specified in the act; in fact, since 1977, they have continued to drop in constant dollars.

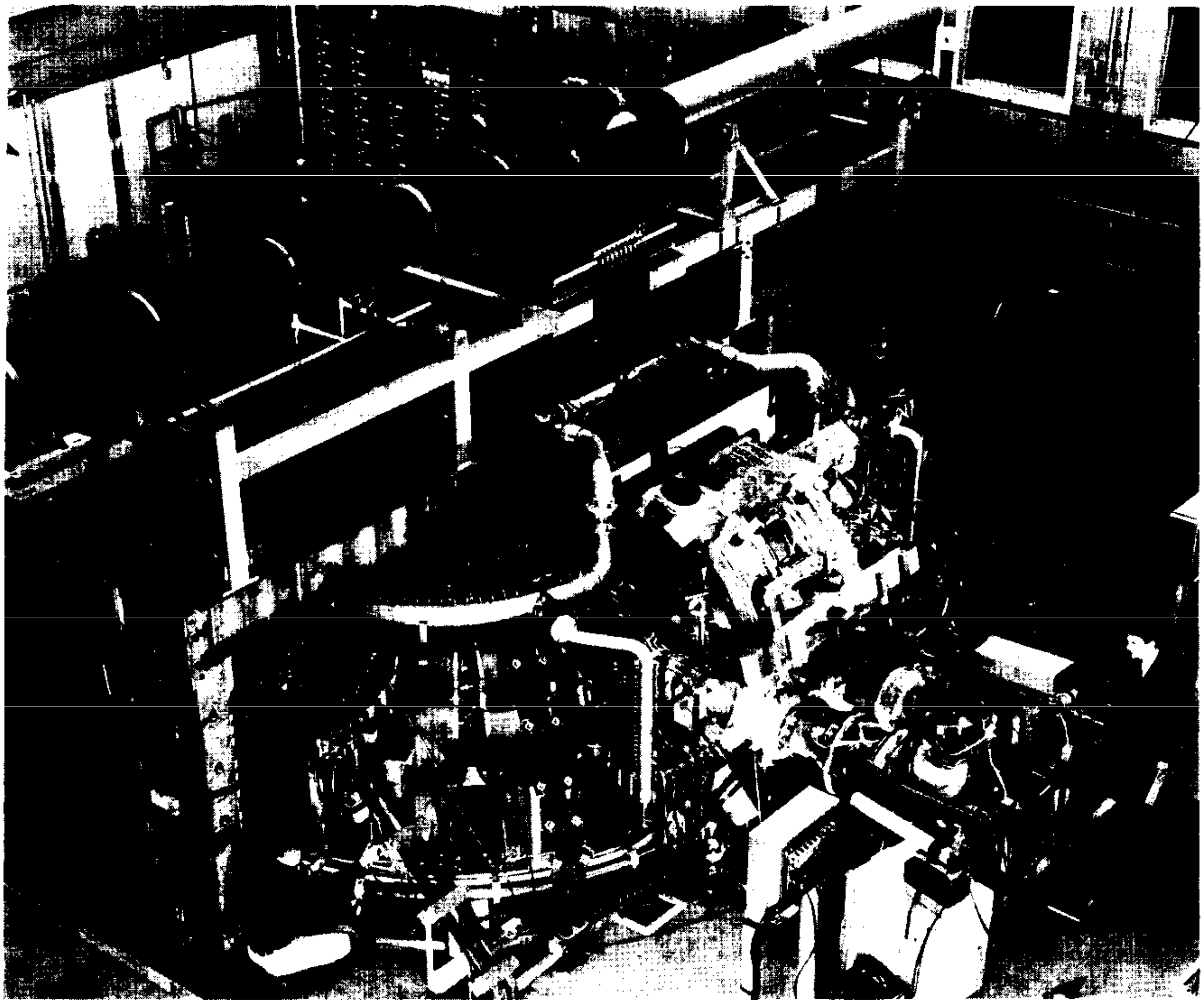


Photo credit: Princeton Plasrna Physics Laboratory

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.

Despite constrained funding, the U.S. fusion program has made significant advances in plasma physics and fusion technology throughout the 1980s. However, DOE has had to adjust its long-range planning to the new fiscal situation. In 1985, it issued the Magnetic Fusion Program Plan (MFPP), which states that the goal of the fusion program is to establish the scientific and technological base required for fusion energy. This plan explicitly recognizes that:

> . . . although the need for and desirability of an energy supply system based on the nuclear fusion principle have not diminished, there is less urgency to develop such a system.[1]

The plan emphasizes the importance of international collaboration if the United States is to establish fusion's technological feasibility during the early 21st century.

The history of U.S. magnetic confinement fusion research is discussed in chapter 3 of this report.

[1] U.S. **Department of Energy, Office of Energy Research,** *Magnetic Fusion Program P/an, DOE/ER-0214,* **February 1985, preface.**

FUSION SCIENCE AND TECHNOLOGY

Great scientific progress has been made in the field of fusion research over the past 35 years. The fusion program appears to be within a few years of demonstrating breakeven, an event that will show an impressive degree of understanding and technical capability. Nevertheless, many scientific and technological issues must be resolved before fusion reactors can be designed and built. The principal scientific uncertainties involve what happens to a plasma when it generates appreciable amounts of fusion power. Because no existing devices can produce significant amounts of power, this uncertainty currently cannot be explored. Simply reaching breakeven will not resolve the uncertainties, since the effects of internally generating fusion power will not be fully realized under breakeven conditions. An ignited plasma, or at least one with high energy gain, must be studied. Issues to be resolved before fusion's technological feasibility can be established are discussed more fully in chapter 4.

Confinement Concepts

Besides the behavior of ignited plasmas, the characteristics, advantages, and disadvantages of various confinement concepts need further study. Several different concepts, utilizing different configurations of magnetic fields and different methods of generating the fields, are being studied (table l-l).

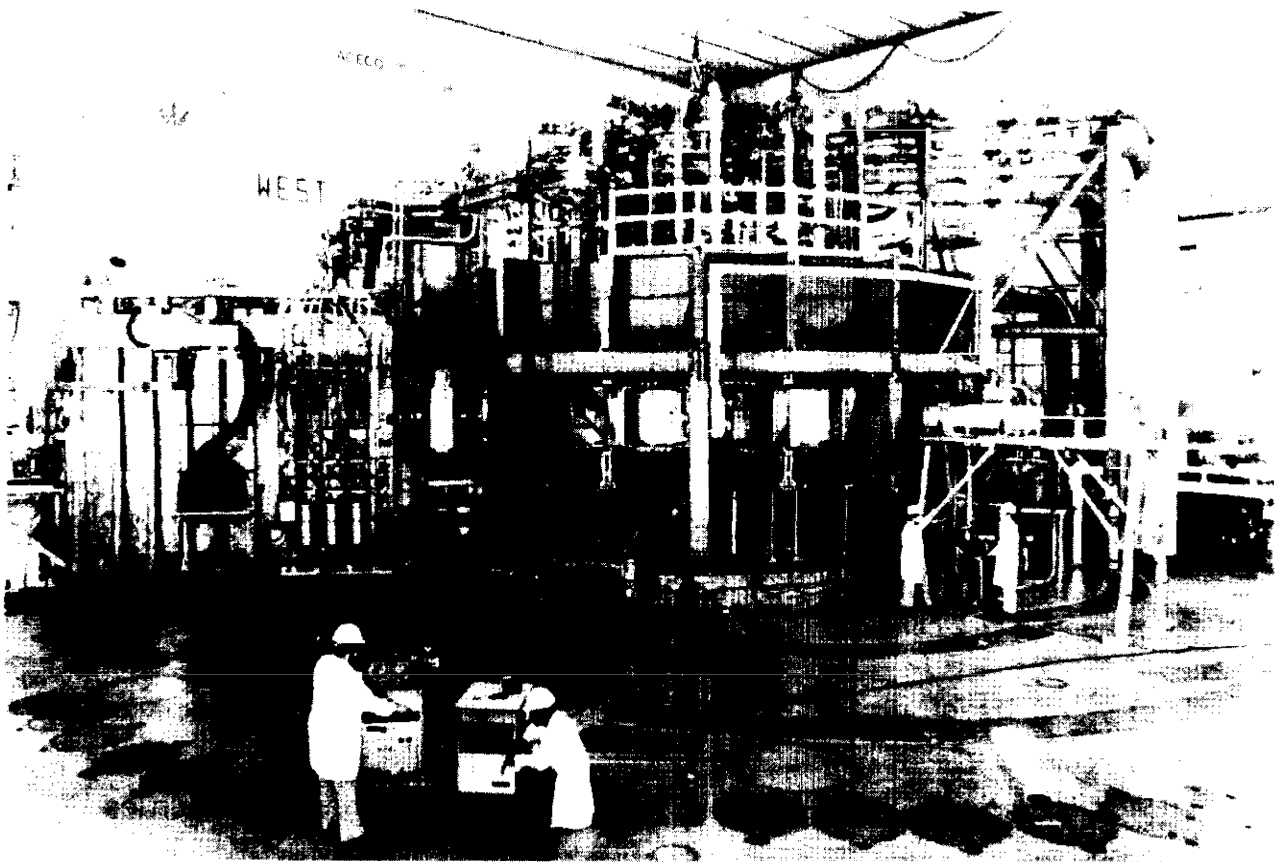


Photo credit: Princeton Plasma Physics Laboratory

The Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory, where breakeven experiments are scheduled for 1990.

Table 1-1.—Classification of Confinement Concepts

Well-developed knowledge base	Moderately developed knowledge base	Developing knowledge base
Conventional Tokamak	Advanced Tokamak Tandem Mirror Stellarator Reversed-Field Pinch	Spheromak Field-Reversed Configuration Dense Z-Pinch

SOURCE: Adapted from 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, p. 15.

At this stage of the research program, it is not known which confinement concepts can form the basis of an attractive fusion reactor. The tokamak is the most developed concept, and it has attained plasma conditions closest to those required in a fusion reactor. Its experimental performance has been encouraging, and it provides a standard for comparison to other concepts. Studies of reactor-like plasmas must be done in tokamaks because no other concept has yet demonstrated the potential to reach reactor conditions. Most fusion technology development takes place in tokamaks as well. Although tokamak behavior has not yet been fully explained theoretically, it may well be possible to design reactor-scale tokamaks on the basis of experimental performance in smaller tokamaks.

Research on alternatives to the tokamak continues because it is not clear that the tokamak will result in the most attractive or acceptable fusion reactor. Moreover, research conducted on different concepts provides important insights into the fusion process. It remains to be seen which alternate concepts will be able to reach the level of performance already attained by the tokamak, whether their relative strengths will be preserved in the development process, and what the costs of developing these concepts to reactor scale will be. Nor is it known what the ultimate capability of the tokamak concept will be.

Reactor Development

Just as an automobile is much more than spark plugs and cylinders, a fusion reactor will contain many systems besides those that heat and confine the plasma. Fusion's overall feasibility will depend on all of the "engineering details" that support the fusion reaction, convert the power released in the reaction into usable energy, and ensure safe, environmentally acceptable operation. Developing and building these associated systems and integrating them into a reactor will require a technological development effort at least as impressive as the scientific challenge of understanding and confining fusion plasmas.

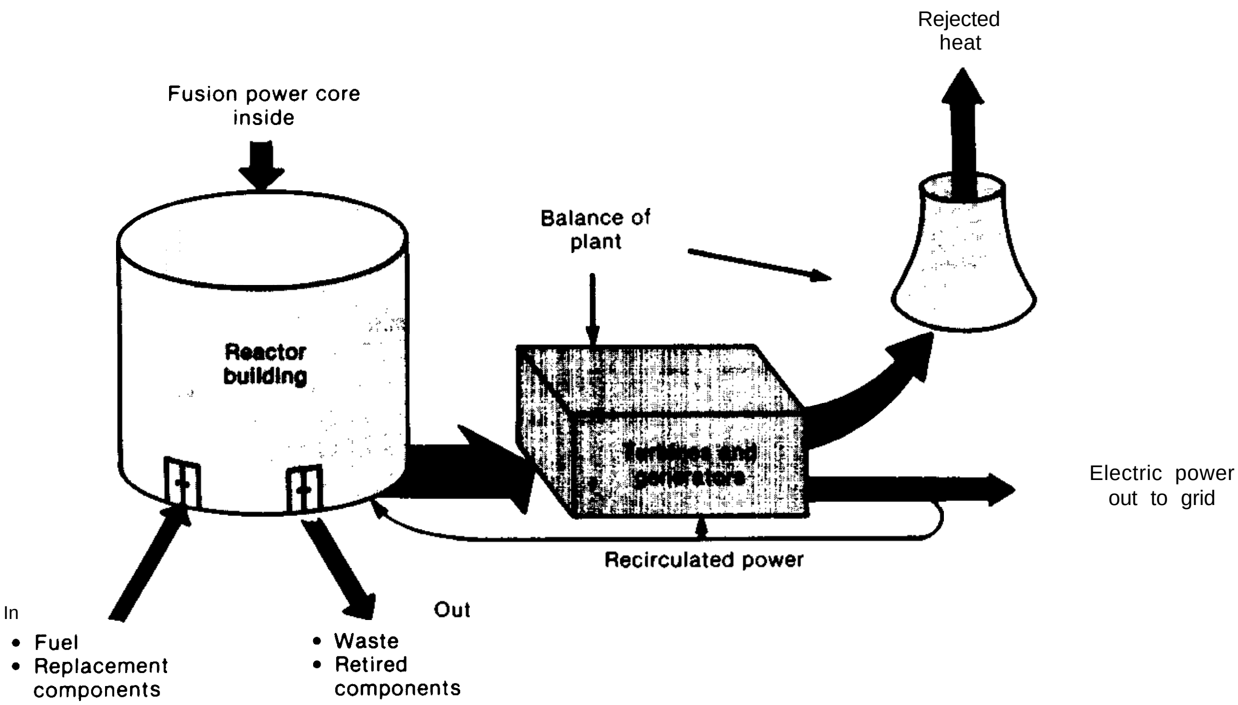
The overall fusion generating station (figure 1-4) consists of a *fusion power core,* which contains the systems that support and recover energy from the fusion reaction, and the *balance of p/ant,* which converts this energy to electricity. Fusion reactor conceptual designs typically have balance of plant systems similar to those found in existing electricity generating stations. However, fusion technology may permit more advanced systems to generate electricity in a manner that is qualitatively different from the methods in use today.

The fusion power core, shown schematically in figure 1-5, is the heart of a fusion generating station. The systems in the core create and maintain the plasma conditions required for fusion reactions to occur. These technologies confine the plasma, heat and fuel it, remove wastes and impurities, and, in some cases, drive electric currents within the plasma. Other systems in the fusion power core recover heat from the fusion reactions, breed fuel, and provide shielding. One of the key requirements for many of these fusion power core systems is the development of suitable materials that are resistant to the intense neutron radiation generated by the plasma. The environmental and safety aspects of fusion reactors depend significantly on materials choice.

Future Plans and Facilities

Many additional experiments and facilities will be required to investigate both scientific and technological aspects of fusion. Preliminary experiments that investigate the basic characteristics of

Figure 1=4.—Systems in a Fusion Electric Generating Station



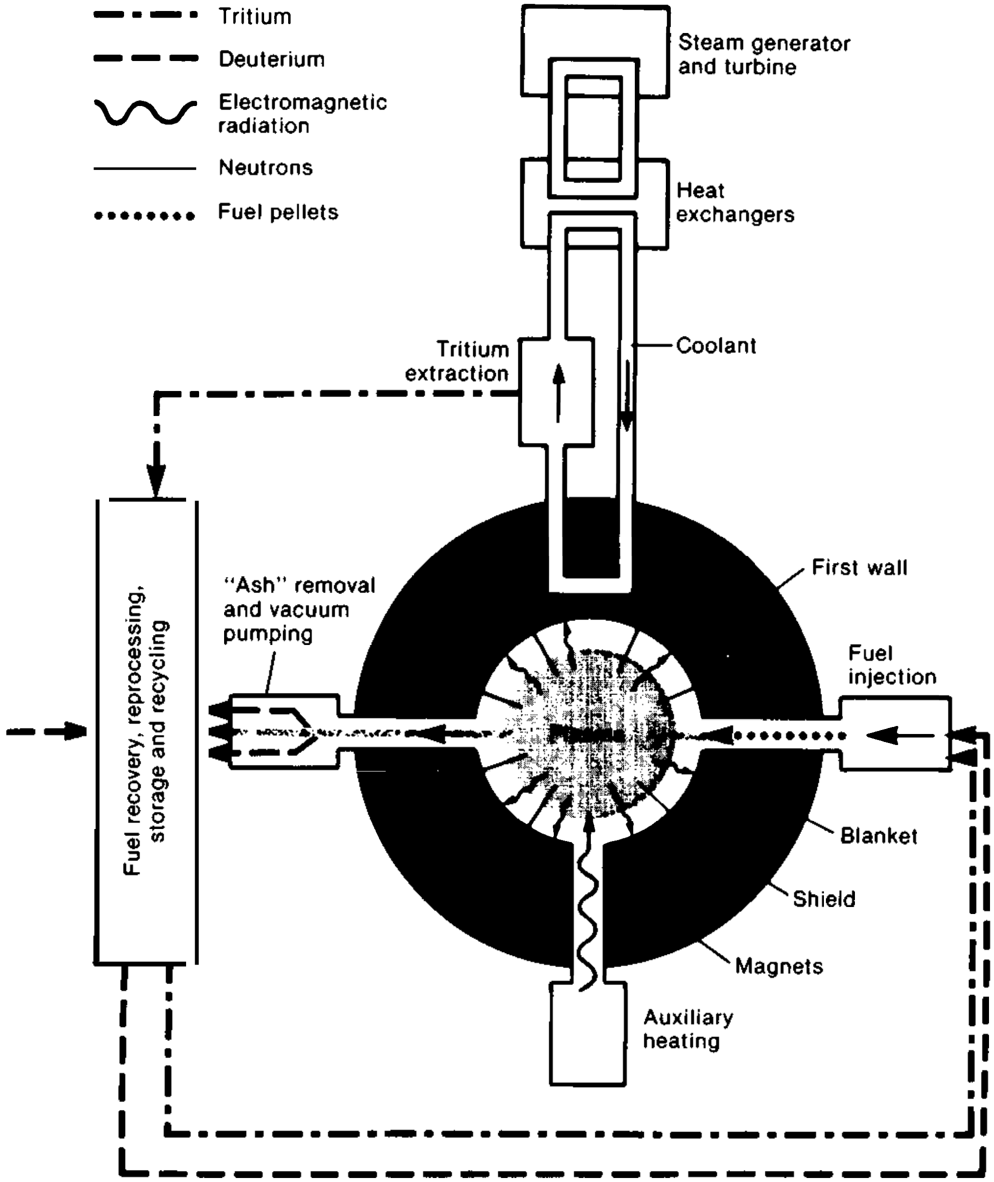
SOURCE: Office of Technology Assessment, 1987.

new confinement concepts can be done for a few million dollars or less. As concepts approach reactor capability, successively larger facilities are required, with reactor-scale experiments costing hundreds of millions of dollars each. Obviously, the U.S. fusion program cannot afford to investigate every confinement concept at the reactor scale; choices must be made on the basis of information gathered at earlier stages.

Additional facilities will be required to resolve general issues not identified with specific confinement concepts. In particular, facilities will be needed to address the scientific issues associated with ignited plasmas. Many physical processes associated with ignition can be studied in ignited plasmas that only last for a few seconds; other aspects, such as fueling and removal of reaction products, will require a facility that can produce ignited plasmas lasting hundreds of seconds. Short- and long-burn ignition questions can be studied either in a single device or in two separate devices. DOE has chosen to separate them, and it has requested funds in its 1988 budget to build a short-pulse ignition facility, called the Compact Ignition Tokamak (CIT). Total costs for this device are estimated at about $360 million.

CIT cannot satisfy the requirements for long pulses, materials studies, or nuclear technology testing. These needs could be addressed in separate facilities and later combined (except for materials testing) in a device that would integrate all the systems for the first time. Alternatively, many of these issues could be addressed and integrated simultaneously in a next-generation engineering test reactor. Satisfying a number of purposes simultaneously would complicate an engineering test reactor's design and could force trade-offs between the different objectives. Moreover, it is likely that each additional requirement will increase the price of the machine. Even so, a general-purpose engineering test reactor would presumably cost less than the combination of several single-purpose facilities and a subsequent system-integration device.

Figure 1-5.—Systems in the Fusion Power Core



SOURCE: Modified from "The Engineering of Magnetic Fusion Reactors, " by Robert W. Corm. Copyright © 1983 by Scientific American, Inc. All rights reserved

DOE has not yet determined the features to be included in an engineering test reactor. It is committed to investigating the possibility for international cooperation on the device; the U.S. Government has proposed to the other major world fusion programs that collaborative conceptual design of such a device, called the International Thermonuclear Experimental Reactor (ITER), be undertaken.

Materials testing will require a dedicated device even if a general-purpose engineering test reactor is built. To complete lifetime irradiation testing of reactor materials in a reasonable

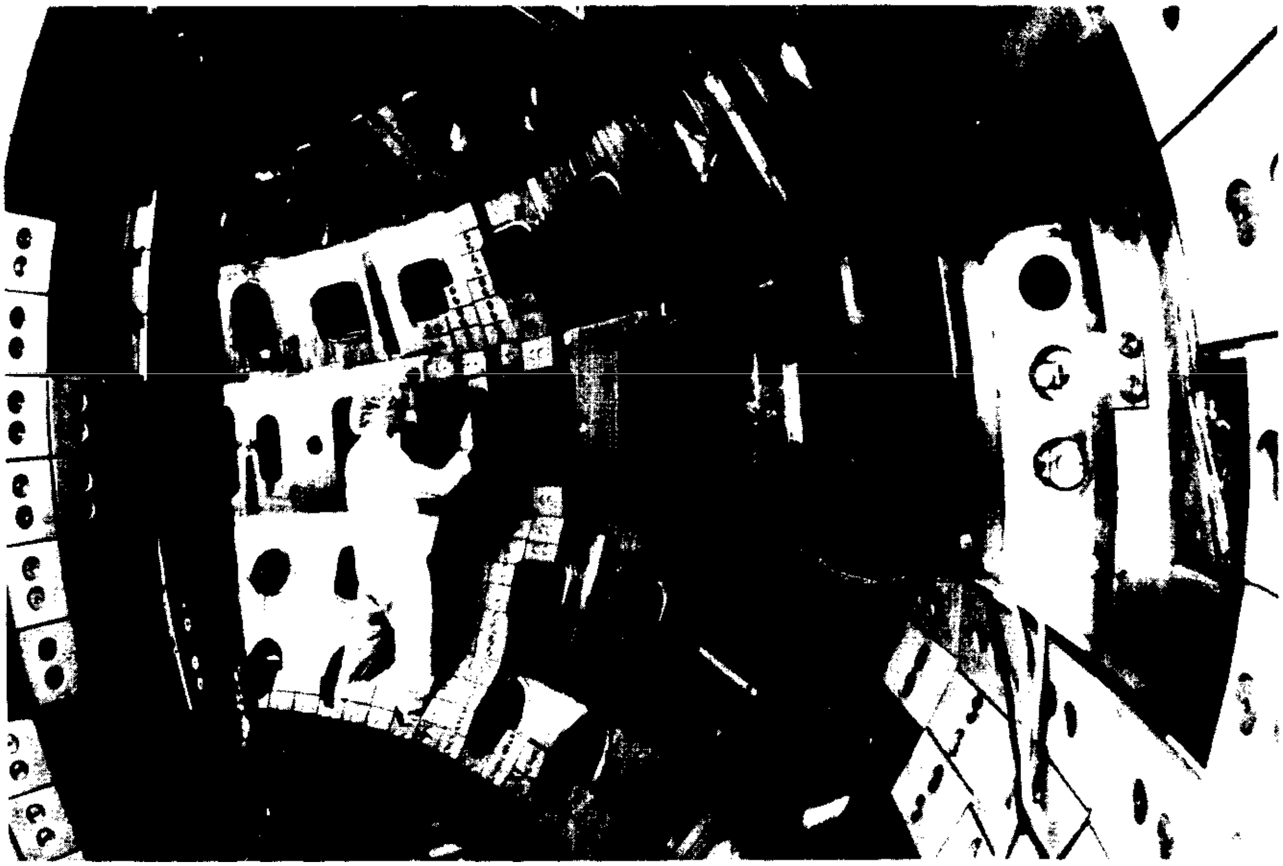


Photo credit” GA Technologies

View inside vacuum vessel of D II I-D fusion device at GA Technologies, San Diego, CA. The plasma is contained within this vessel.

amount of time, a source of fusion neutrons several times more intense than expected from a commercial reactor is required. While an engineering test reactor would duplicate conditions expected in a reactor, it would not be able to conduct accelerated materials tests at several times the radiation levels to be found in a reactor.

Schedules and Budgets

A major fusion-communitywide study has identified the technical tasks and facilities required to establish fusion's technological feasibility and enable a decision to be made early in the next century to start the commercialization process,[2] The study estimated that the worldwide cost of this research effort would be about $20 billion. As mentioned earlier, developing fusion on this schedule will require either substantially increased U.S. funding or wide-scale collaboration among the world fusion programs.

The requirements and schedule for establishing fusion's subsequent commercial feasibility are more difficult to project, and they depend on factors other than fusion research funding. Conceivably, if the research program provides the information necessary to design and build a reactor prototype, such a device could be started early in the next century. After several years of construction and several more years of qualification and operation, a base of operating experience could be acquired that would be sufficient for the design and construction of commercial devices.

[2]Argon ne National Laboratory, Fusion Power Program, *Technical f'/anning Activity: Final Report,* commissioned by DOE, Office of Fusion Energy (OFE), AN L/FPP-87-I, 1987,

If the regulatory and licensing process proceeded concurrently, vendors and users could begin to consider manufacture and sale of commercial fusion reactors sometime during the middle of the first half of the next century. From that point, it will take decades for fusion to penetrate energy markets. **Even under the most favorable circumstances, it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century.**

This schedule for demonstrating technological and commercial feasibility requires a number of assumptions. Sufficient financial support or international coordination must be attained so that the research needed to establish technological feasibility can be completed early in the next century. Research must proceed without major difficulty and must lead to a decision to build a reactor prototype. The prototype must operate as expected and prove convincingly that fusion is both feasible and preferable to its alternatives.

Photo credit: JET Joint Undertaking

The Joint European Torus, located in Abingdon, United Kingdom.

Status of the World Programs

The United States, Western Europe, Japan, and the Soviet Union all have major programs in fusion research that are at similar stages of development. Each program has built or is building a major tokamak experiment. The U.S. Tokamak Fusion Test Reactor and the European Community's Joint European Torus are operating and are ultimately intended to reach breakeven conditions with D-T fuel. Japan's JT-60 tokamak, also operational, will not use tritium fuel; it is intended to generate a "breakeven-equivalent" plasma using ordinary hydrogen and deuterium. The Soviet Union's T-1 5 experiment is under construction. In addition to these major devices, each of the programs operates several smaller fusion experiments that explore the tokamak and other confinement concepts. Each program is also developing other aspects of fusion technology.

FUSION AS AN ENERGY PROGRAM

The long-term goal of the fusion program in the United States is to produce electricity. Fusion reactors can also produce fuel for fission reactors by irradiating suitable materials with neutrons, but this ability is not seen as fusion's primary application in the United States, Western Europe, or Japan. (The Soviet fusion effort does appear oriented towards producing fuel for fission reactors .)[3]

[3] A fusion reactor that produces fissionable fuel, or one that generates part of its energy from fission reactions that are induced by fusion-generated neutrons, is called a *fission/fusion hybrid* reactor. Although the applications and characteristics of hybrid reactors are different from those of "pure fusion" reactors that do not use or

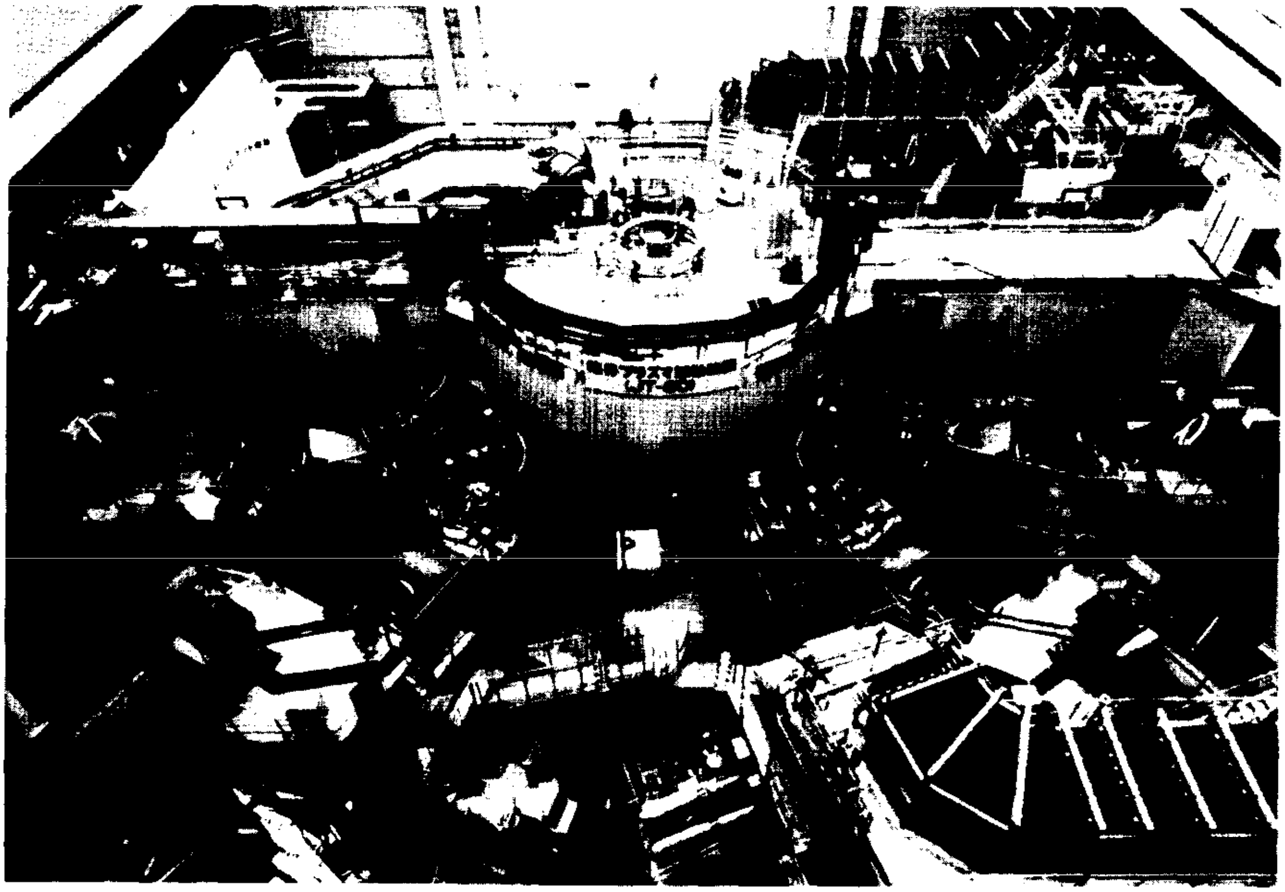


Photo credit; Japanese Atomic Energy Research Institule

The JT-60 tokamak, located in Naki-machi, Japan.

Hypothetical designs for fusion reactors that produce electricity have been studied for a numbet of years. Since the research program is far from complete, however, current systems studies are necessarily tentative. Although these studies have been especially valuable in identifying improvements in fusion physics or technology that appear to have the greatest potential for making fusion reactors attractive and competitive, they cannot provide a firm basis for assessing fusion's potential as a future energy source. Nevertheless, the studies do provide a basis for projecting the possible characteristics of fusion reactors. These projections will improve as additional knowledge and understanding enable scientists and engineers to better model the reactor systems. Chapter 5 of this report discusses projected characteristics of fusion reactors, along with the factors that will determine the degree to which fusion is accepted in the energy marketplace.

Safety

If fusion development is successful, it maybe possible to ensure that accidents due to malfunctions, operator error, or natural disasters could not result in immediate public fatalities. This safety would depend on passive systems or on materials properties, rather than on active systems that could fail or be overridden. A number

produce fissionable materials, there is little difference at present ın the research requ I red to develop the two. Differences wil I arise at subsequent stages of research and development.

This assessment focuses on pure fusion reactors; hybrid reactors are discussed briefly in app. A of the full report, of attributes of the fusion process should make safety assurance easier for fusion reactors than for fission reactors:

- Fusion reactions cannot run away. Fuel will be continuously injected, and the amount contained inside the reactor chamber will only operate the reactor for a short period of time. Energy stored in the plasma at any given time can be dissipated by the vacuum chamber in which the fusion reactions take place.
- With appropriate choice of materials, the amount of heat produced by the decay of radioactive materials in the reactor after the reactor has been shut down should be less for fusion reactors than for fission reactors. Fusion reactors should therefore require simpler post-shutdown or emergency cooling systems, if any such systems are required at all.
- The radioactive inventory of a fusion reactor —in terms of both the total amount present in the reactor and the fraction that would be likely to be released in an accident–should be smaller than that of a fission reactor. Fusion will not generate long-lived wastes such as those produced by fission reactors. Except for tritium gas, the radioactive substances present in fusion reactors will generally be bound as metallic structural elements.
- in the event of accidental release, fusion reactors should not contain radioactive elements —except tritium —that would tend to be absorbed in biological systems. Tritium is an inherent potential hazard, but the risk it poses is much smaller than that of the gaseous or volatile radioactive byproducts present in fission reactors, Active tritium inventories in current fusion reactor designs are small enough that even their complete release should not produce any prompt fatalities off-site. Moreover, fusion reactors operating on advanced fuel cycles would not need tritium.

This discussion does not imply that fission reactors are unsafe. indeed, efforts are underway to develop fission reactors whose safety does not depend on active safety systems. However, the potentially hazardous materials in fission reactors include fuels and byproducts that are inherent to the technology. While the tritium fuel required by a D-T fusion reactor is a potential hazard, the byproducts of fusion are not in themselves hazardous, Since there is much greater freedom to choose materials that minimize safety hazards for fusion reactors than there is in fission reactor design, a higher degree of safety assurance should be attainable with fusion.

Environmental Characteristics

Fusion reactors will not be free of radioactive wastes, although the wastes that they produce should be easier to dispose of than fission wastes. Fusion reactors will not generate the long-lived and highly radioactive wastes contained in the spent fuel rods of fission reactors. Fusion wastes may have a greater physical volume than fission wastes, but they should be substantially less radioactive and orders of magnitude less harmful. The amount of radioactive waste anticipated from different fusion designs ranges over several orders of magnitude because it depends on the choice of materials with which the reactor is made. Special materials that do not generate intense or long-lived radioactive wastes may be developed that would make it possible to substantially reduce the radioactive waste produced by a fusion reactor.

Nuclear Proliferation Potential

The ability of a fusion reactor to breed fissionable fuel could increase the risk of nuclear proliferation. Proliferation concerns relate to the possibility of constructing fission-based or atomic weapons. Although fusion reactors contain tritium, a material that could be used in principle to make thermonuclear weapons such as the hydrogen bomb, such weapons cannot be built by parties who do not already possess fission weapons.

A reactor deriving all its energy from fusion and producing only electricity would not contain materials usable in fission-based nuclear weapons, and it would be impossible to produce such materials by manipulating the reactor's normal fuel cycle. However, material usable in fission weapons could be produced by placing other materials inside the reactor and irradiating them with fusion neutrons. This procedure, in effect, would convert a pure fusion reactor into a fission/fusion hybrid reactor (see note 3, above). If such modifications to the reactor structure were easily detected or were extremely difficult and expensive, pure fusion reactors would be easier to safeguard against surreptitious production of nuclear weapons material than existing fission reactors, and fusion reactors would therefore pose less of a proliferation risk.

Resource Supplies

Shortage of fuels will not constrain fusion's prospects for the foreseeable future. Enough deuterium is contained in the earth's waters to satisfy energy needs through fusion for billions of years at present consumption rates. Domestic lithium supplies should offer thousands of years worth of fuel, with vastly greater amounts of potentially recoverable lithium contained in the oceans.

Materials required to build fusion reactors may pose more of a constraint on fusion's development than fuel supply, but at this stage of research it is impossible to determine what materials will eventually be developed and selected for fusion reactor construction. No particular materials other than the fuels appear at present to be indispensable for fusion reactors.

cost

It is currently impossible to determine whether a fusion reactor, once developed, will be economically competitive with other energy technologies. The competitiveness of fusion power will depend not only on successful completion of the remaining research program but also on additional factors that are impossible to predict—e.g., plant licensability, construction time, and reliability, not to mention factors less directly related to fusion technology such as interest rates. Fusion's competitiveness will also depend on technical progress made with other energy technologies.

Fusion's Energy Context

The factors that influence how successfully fusion technology will compete against other energy technologies include how well its characteristics meet the requirements of potential customers (most likely electric utilities) and how well fusion compares to alternate electricity-generating technologies. A more detailed look at these factors makes a number of points clear:

- **The overall size and composition of electricity demand, by itself, should neither require nor eliminate fusion as a supply option.** Supplies of both coal and uranium appear adequate at reasonable prices to meet high future demand in the absence of fusion.[4] It will be overall economics and acceptability, rather than total demand or fuel availability, which will determine the mix of energy technologies.
- **It is unlikely that any one technology will take over the electricity supply market, barring major difficulties with the others.**
- **Potential problems with currently foreseen future sources of electricity provide incentives to develop alternate energy technologies and/or substantially improve the efficiency of energy use.** Combustion of coal releases carbon dioxide, whose accumulation in the atmosphere may affect world climate; this problem may make increased reliance on coal undesirable. Safety, nuclear waste, or nuclear proliferation concerns may continue to impair expansion of the nuclear fission option. **The urgency for developing fusion, therefore, depends on assumptions of the likelihood that existing energy technologies will prove undesirable in the future.**

[4] Coal supplies are adequate to provide power for centuries at current rates of use. Uranium supplies should be available at a reasonable price until well into the next century without requiring either breeder reactors or reprocessing. Advanced, more efficient fission reactors could delay the need for breeders or reprocessing still further. With the use of breeders, uranium deposits become adequate for centuries.

- **There is little to be gained and a great deal to be lost if fusion is prematurely introduced without attaining its potential economic, environmental, and safety capabilities.** Even in a situation where problems with other energy technologies urgently call for development of an alternative source of supply, that alternative must be preferable in order to be accepted, It would be unwise to emphasize one fusion feature—economics or safety or environmental advantages—over the others before we know which aspect will be most important for fusion's eventual acceptance.

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 near-term, non-energy benefits. These benefits fall in four major categories.

Near-Term Benefits

1. Development of Plasma Physics

Plasma physics as a branch of science began in the 1950s, driven by the needs of scientists working on controlled thermonuclear fusion and, later, by the needs of space science and expiration. The field of plasma physics has developed rapidly and has synthesized many areas of physics previously considered distinct disciplines. Magnetic fusion research funding is crucial to the continuation of plasma physics research; over half of all Federal plasma physics research is funded by the magnetic fusion program.

2. Educating Scientists

Educating scientists and engineers is one of the most widely acknowledged benefits of the fusion program. Over the last decade, DOE's magnetic fusion energy program has financed the education of most of the plasma physicists produced in the United States. DOE, through its magnetic fusion program, directly supports university fusion programs and provides 37 fusion fellowships annually to qualified doctoral students. Training in plasma physics enables these scientists to contribute to defense applications, space and astrophysical plasma physics, materials science, applied mathematics, computer science, and other fields.

3. Advancing Science and Technology

Many high-technology research and development (R&D) programs produce secondary benefits or "spin -offs." Over the years, the magnetic fusion energy program has contributed to a variety of spin-off technologies with wide-ranging applications in other fields. Among them are superconducting magnet technology, high-quality vacuums, high-temperature materials, high-frequency and high-power radiofrequency waves, electronics, diagnostics and tools for scientific analysis, high-speed mainframe computers, and particle beams. 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. It is impossible to predict before-the-fact which research investments will have the greatest spin-off return.

4. 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 began 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 Financial and Personnel Needs

Financial Resources

The Federal R&D budget has grown steadily in the 1980s. The bulk of this growth has been driven by increases in defense spending, but non-defense R&D has also grown. The fraction of the Federal R&D budget devoted to energy, however, has been steadily declining during the 1980s. In fiscal year 1987, energy R&D is estimated to account for less than 4 percent of the Federal R&D budget.

virtually all fusion research is funded by the Federal Government; due to fusion's long-term, high-risk nature, there is little private sector investment. Even though the fusion budget has fallen, in constant dollars, to less than half of its 1977 peak, magnetic fusion has fared better than many other energy programs. DOE's energy programs in nuclear fission, fossil fuels, conservation, and renewable energy technologies have lost proportionately more of their Federal support because it is believed that private sector financing is more appropriate in these cases. Figure 1-6 shows the budgets of DOE's larger energy R&D programs during the 1980s.

Personnel Resources

The fusion program currently supports approximately 850 scientists, 700 engineers, and 770 technicians.[5] These researchers work primarily at national laboratories and in university and college fusion programs. According to estimates by DOE, the number of Ph.D. staff positions in the fusion program has declined by almost 20 percent since 1983. Most of the fusion researchers who have left the fusion program have found work in other research programs within DOE and the Department of Defense. Many former fusion researchers, for example, are working on Strategic Defense Initiative projects,

[5]Thomas G. Finn, 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.

Participation in the Magnetic Fusion Program

The Department of Energy's Office of Fusion Energy (OFE) conducts research through 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.

National Laboratories

It is estimated that national laboratories will conduct over 70 percent of the magnetic fusion R&D effort in fiscal year 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."[6] Four laboratories conduct the bulk of the Nation's fusion research: Lawrence Livermore National Laboratory in Livermore, CA; Los Alamos National Laboratory in Los Alamos, NM; Oak Ridge National Laboratory in Oak Ridge, TN; and Princeton Plasma Physics Laboratory in Princeton, NJ.

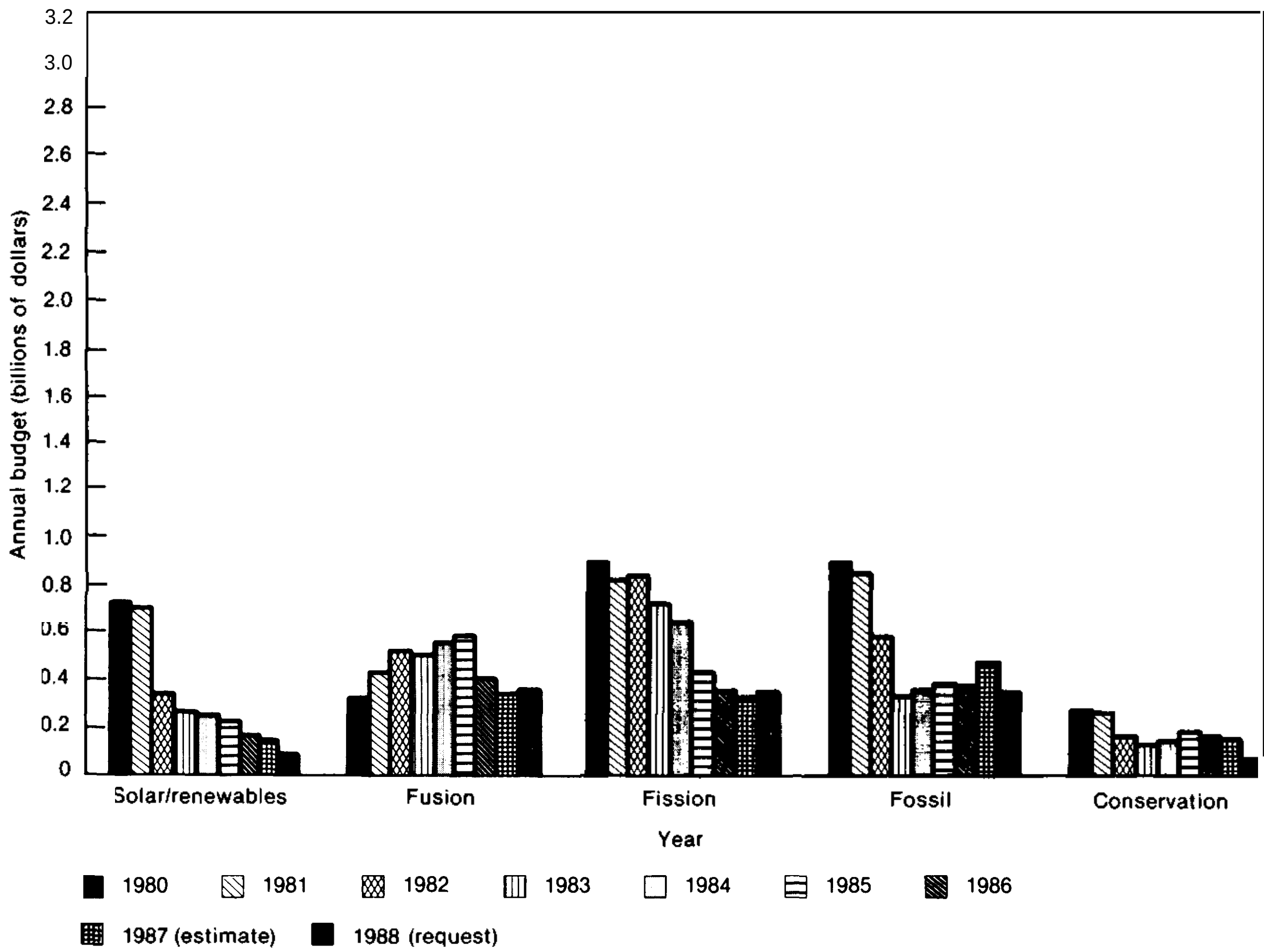
Universities and Colleges

Within the fusion program, universities and colleges provide education and training and historically have been a major source of innovative ideas as well as scientific and technical advances. It is estimated that the university and college programs will receive about 11 percent of the Federal fusion budget directly in fiscal year 1987. In addition, they will probably receive another 2 or 3 percent through the national laboratories.

Recent budget cuts have seriously affected university and college fusion programs. Over 80 percent of these programs have budgets of less than $1 million, and there are no other sources of Federal funding for fusion research to replace DOE appropriations. Since 1983, two-thirds of the university and college fusion programs have reduced or eliminated their programs. The University Fusion Associates, an informal grouping of individual researchers from universities and col-

[6]John F. Clarke, Director of the DOE Office of Fusion Energy, "Planning for the Future," *Journal of Fusion Energy, vol. 4, Nos. 2/3,* June 1985, p. 202.

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



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

leges, anticipates that as many as half of the institutions represented by its members will eliminate their fusion programs between 1986 and 1989 if the university fusion budgets are not maintained. DOE, however, disputes this claim and projects constant budgets (corrected for inflation) for the university programs.

Private Industry

private industry can take a variety of different roles in fusion research, depending on its level of interest in the program and the status of fusion development. At the lowest level, industry can serve as an advisor to DOE and the national laboratories. As the research approaches the engineering stage, industry can begin to participate directly by supplying components or contracting with DOE. Ultimately, it is anticipated that industry will sponsor research and development activities.

To date, industry and utility involvement in magnetic fusion R&D has been advisory, with limited cases of direct participation. This is due largely to fusion's long time horizon and the lack of predictable, easily commercializable "spin-off" technologies. Most current industrial participation is facilitated through subcontracts from national laboratories.

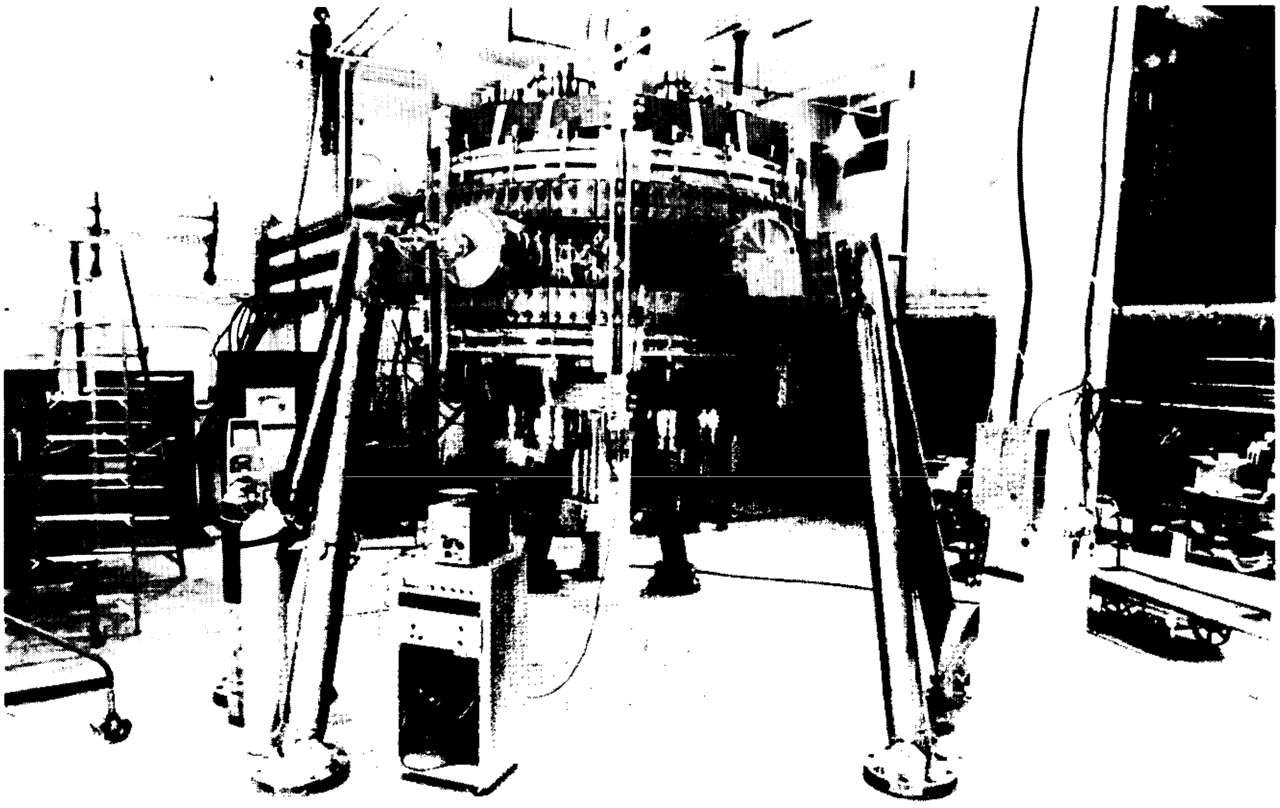


Photo credit: Plasma Fusion Center, MIT

The Alcator C tokamak at the Massachusetts Institute of Technology.

The transition of responsibility for fusion research and development from government to industry is a significant hurdle to be cleared before fusion can be commercialized. Current DOE policy calls for any demonstration fusion reactor to be built and operated by the private sector. Industries and utilities, on the other hand, may be unwilling to risk a major investment in a new and unproven technology.

There is considerable controversy over the appropriate time for the private sector to become more involved in the research program. Some argue that the willingness of industry to invest in fusion technology should not be used as a criterion for determining its appropriate degree of involvement. They maintain that early involvement of industry in fusion research is necessary to ensure that the technology will be attractive to its eventual users and marketable by the private sector. Others counter that, given present and foreseeable future research budgets, there are not enough opportunities for the private sector to develop and maintain a standing capability in fusion. These individuals believe that industry's limited participation in fusion research in the near-term will not preclude its eventual role in demonstration and commercialization.

Chapter 6 of this report describes characteristics of fusion as a near-term research program—its near-term benefits, its financial and personnel needs, and its principal participants.

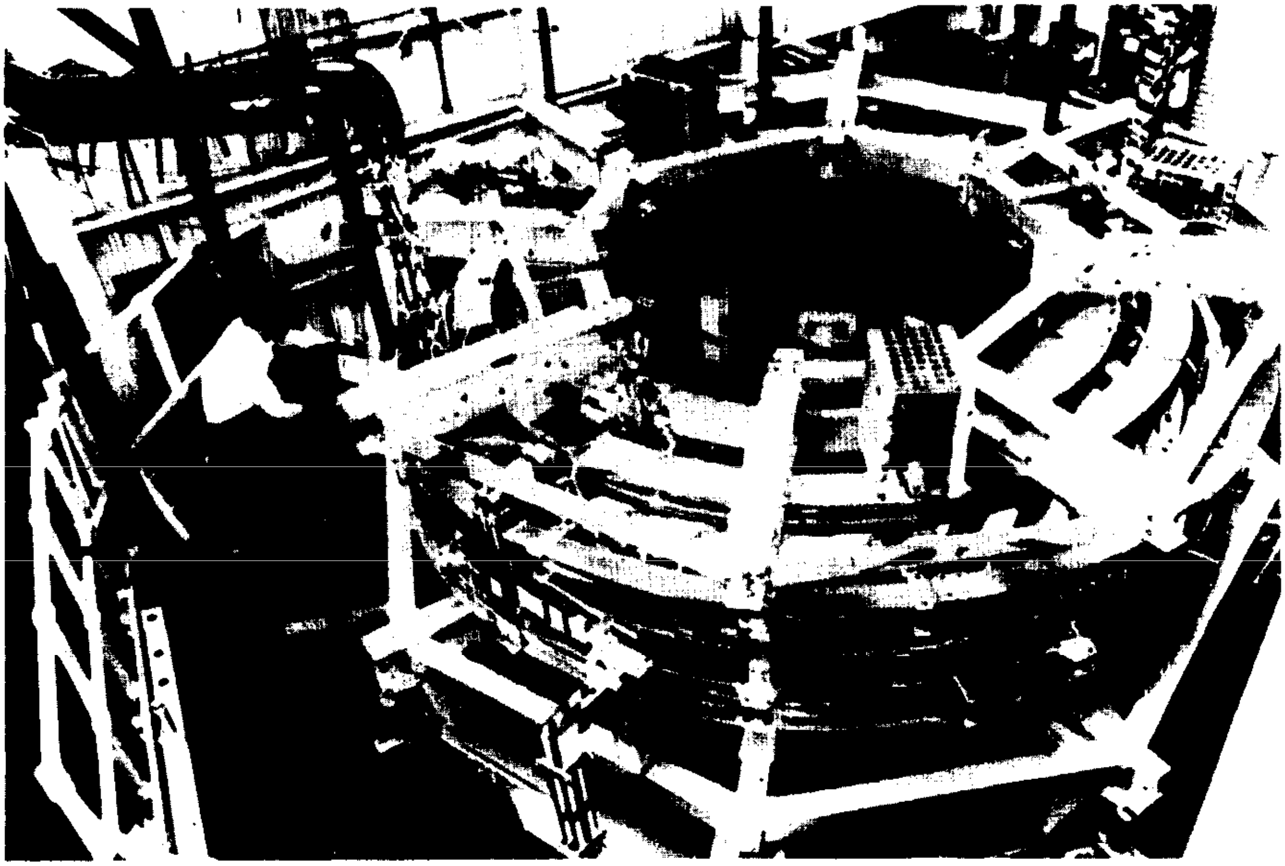


Photo credit: GA Technologies

The Ohmically Heated Toroidal Experiment at GA Technologies, Inc., which is the only major fusion experiment constructed and operated largely with private funds.

FUSION AS AN INTERNATIONAL PROGRAM

The field of magnetic fusion research has a 30-year history of international cooperation. The leaders of the U.S. fusion community continue to support cooperation, as does DOE. In the past, the United States cooperated internationally in a variety of exchanges that have produced useful information without seriously jeopardizing the autonomy of the domestic fusion program. In recent years, in response to budgetary constraints and the technical and scientific benefits of cooperation, DOE has begun cooperating more intensively in fusion, and the major fusion programs have become more interdependent. For the future, DOE proposes undertaking cooperative projects that will require the participating fusion programs to become significantly interdependent: **indeed, DOE now sees more extensive international cooperation as a financial necessity.**

Opportunities for Increased Collaboration

Cooperation among the major world fusion programs can be expected to continue at its current level, at the least, as long as each of the major fusion programs maintains a level of effort sufficient to make it an attractive partner to the others. In the future, it is also possible that a substantially expanded degree of collaboration may take place. Such collaboration may take two forms:

joint construction and operation of major facilities on a scale not yet attempted among the four programs, and substantial additional joint planning among the world programs to minimize redundant research and to maximize the transfer of information and expertise among the programs.

Those who favor increased levels of collaboration believe that there will be important opportunities over the next decade. At the same time that similarities in the status and goals of the major international fusion programs provide a technical basis for expanded cooperation, the comparable levels of achievement ensure that each program can contribute to and benefit from collaboration. Moreover, commercial applications of fusion technology are sufficiently far off that competitive concerns should be minimal. Since the programs may not remain comparable over the long term, these pro-collaboration observers maintain that the timing may not be as advantageous for collaboration in the future as it is now. In particular, they worry that if recent funding trends continue, the U.S. fusion program may fall behind the other programs and might no longer be viewed as a desirable partner.

Benefits and Liabilities of Cooperation

International collaboration introduces a number of potential benefits and liabilities to the participants. Observers will weigh these features differently, arriving at different conclusions about the value of collaboration:

- **Knowledge Sharing.** All forms of cooperation involve sharing knowledge. Researchers can take advantage of one another's experience, greatly aiding their own progress. Some observers, however, are concerned that collaboration could lead to exchange of information that has adverse implications for national security or technological competitiveness.
- **Cost Sharing.** Cooperation can save the partners money by spreading out the costs of experiments among the participants and avoiding duplication of effort. Some additional costs may be added as a result of increased administrative complexity, but barring unusual circumstances each partner should spend less through collaboration than it would to duplicate the research by itself.
- **Risk Sharing.** The financial and programmatic costs of a collaborative project are spread among a number of participants, minimizing the exposure of any one of them in the event of failure. On the other hand, through collaboration, each party opens itself up to the risk that withdrawal of any of the other partners may jeopardize the success of the entire project. A partner may also become dependent on others for the continuation of its own program. Finally, some observers feel that the absence of competition and duplication among experimental facilities may increase the risk of technical failure.
- **Diplomatic and Political Implications.** Collaboration can be diplomatically motivated, because it may improve relations and increase familiarity between the partners. Some analysts welcome this additional aspect of collaboration; others fear that diplomatic motivations may override technical ones, causing a project to be undertaken that might not be judged attractive on its technical merits alone.
- **Domestic Implications.** If the domestic program is neglected in order to support the collaboration, both the ability of the partner to collaborate and the value of collaboration to that partner may be compromised. Even if the domestic program is not damaged, it will be influenced by participation in collaboration. Becoming dependent on collaboration lessens the flexibility of the partners to change research direction and emphasis. On the other hand, collaboration can stabilize domestic efforts; the additional commitment given to a collaborative effort makes it more difficult for domestic contributions to that effort to be cut back.

Obstacles to International Cooperation

The process of organizing and executing large-scale collaboration presents challenges that must be overcome by each of the partners. Among the challenges will be siting the facility, resolving the technology transfer concerns of the parties and making them compatible with an open exchange of research results, resolving technical differences among the parties, and overcoming a variety of administrative obstacles including different institutional frameworks, different budget cycles, different legal systems, and personnel needs.

Negotiating and executing workable agreements for international collaboration will undoubtedly be a difficult and time-consuming process. Legal and institutional frameworks must be devised that address the issues in a manner acceptable to participants in the project.

The International Thermonuclear Experimental Reactor

Currently, most of the effort in international collaboration is focused on a proposal to develop a conceptual design for an international engineering test reactor, called the International Thermonuclear Experimental Reactor (ITER). Estimates indicate that building an engineering test reactor will cost well over $1 billion and possibly several times this amount, which is far more than the U.S. fusion program has spent on any one facility in the past and is too expensive for the United States to undertake alone without substantial increases in fusion funding. Therefore, DOE is involved in discussions with the other worldwide fusion programs to jointly design, construct, and operate ITER.

At this stage, only the conceptual design of ITER is being considered by the potential collaborators; the U.S. Government recently issued a proposal to begin a joint planning activity on a conceptual design for the experiment, along with supporting R&D. It is anticipated that the conceptual design phase of ITER will occur between 1988 and 1990 at a total estimated cost ranging from $150 million to $200 million. The U.S. cost of the undertaking is projected to be between $15 million and $20 million annually over the 3-year program.

Since the U.S. Government proposal addresses only the conceptual design phase of ITER, it makes no commitment to future construction of a collaborative experiment. Therefore, current negotiations will not address the obstacles to international collaboration that would arise if and when the decision were made to jointly construct and operate the device. At the completion of the conceptual design phase, interested parties would be in a position to begin negotiations on whether or not to proceed with construction. The existence of a conceptual design would make it easier to resolve many of the questions that would arise should a subsequent decision be made to build and operate ITER. In particular, it should be possible to analyze concerns about technology transfer specifically and determine their implications for national security or industrial competitiveness.

International cooperation on the scale required for ITER is unprecedented for the United States. Reaching agreement within the U.S. Government to initiate and maintain support for ITER over the lifetime of the project will probably require a presidential decision. Even that, by itself, is insufficient to guarantee the viability of a project involving all branches of the U.S. Government and extending over several presidential administrations.

At this time, DOE considers international collaboration on the scale of ITER to be crucial. Given the seriousness of the obstacles, however, it is possible that such collaboration may not occur, **In the event that no major collaboration takes place, either the U.S. fusion program will have to be funded at a higher level or its schedule will have to be slowed down and revised.**

International issues are discussed in chapter 7 of this report.