Overview and Findings

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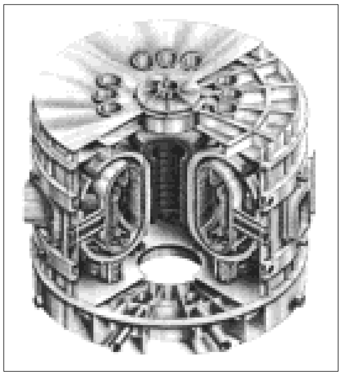
For over four decades the federal government has supported research to develop the power of fusion energy for commercial electric power production. Fusion proponents note that the supply of fusion fuels is virtually inexhaustible, and that environmental impacts may be far less extensive than those of energy supplies currently in widespread use. Widely heralded experiments performed in 1993 and 1994 at the Princeton Plasma Physics Laboratory's Tokamak Fusion Test Reactor (TFTR) produced unprecedented levels of fusion reactions and continued a trend of progress in fusion research.

However, even the most optimistic proponents of fusion energy note that many scientific, engineering, and economic challenges remain to be met. Meeting these challenges sufficiently to construct a prototype commercial fusion powerplant may require several tens of billions of dollars in experimental facilities and research over the next several decades. This would require a considerable increase from the U.S. Department of Energy's (DOE's) current fusion energy program budget of $373 million, and a greater level of cost-sharing through international collaboration in fusion research and development.[1]

In 1987, the Office of Technology Assessment (OTA) concluded a major assessment of the fusion energy program and published the report *Starpower: The U.S. and the International Quest*



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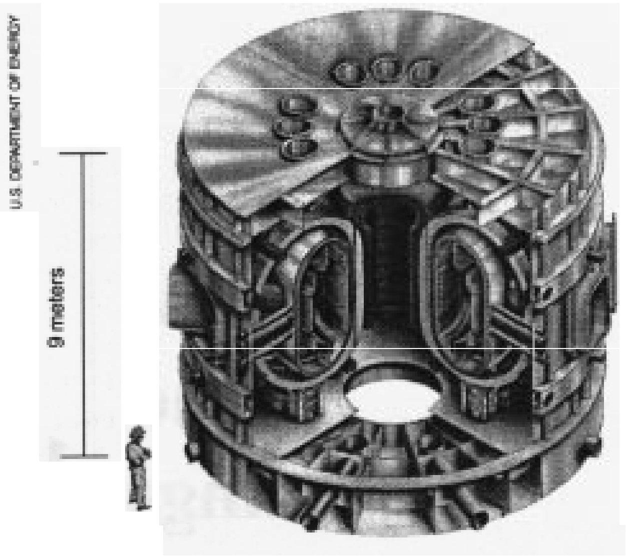
[1] An additional $176 million is spent on inertial confinement fusion research as part of DOE's defense programs, much of which is relevant to fusion energy prospects.



The proposed Tokamak Physics Experiment (TPX).

for Fusion Energy.[2] Since then, the U.S. fusion energy program has undergone a pronounced change as it has grappled with uncertain budgets that have grown less quickly than the need for larger, more capable, and more expensive machines. One result has been a substantial narrowing of efforts to concentrate on the single most successful and furthest developed fusion concept, the tokamak. This narrowing, driven heavily by budgetary reasons, has been decried by many fusion researchers as premature given the current state of fusion knowledge.

This background paper, requested by the House Committee on Science, Space, and Technology,[3] focuses on two issues in the recent and continuing evolution of the U.S. fusion energy research and development (R&D) program:

- **What is the role of the proposed Tokamak Physics Experiment (TPX)?** TPX is an approximately $700-million fusion reactor currently in an advanced stage of engineering design and awaits a congressional decision to begin construction at the Princeton Plasma Physics Laboratory. This paper examines the history of TPX planning and the anticipated scientific, engineering, and institutional contributions of the TPX. It explores the relationship between the TPX and the next major planned tokamak facilities, the International Thermonuclear Experimental Reactor (ITER), currently in the design stage, and the Demonstration Fusion Powerplant (DEMO) facility, planned for operation in about three decades, which would be the first fusion device to demonstrate production of electricity.
- What is **the role of alternatives to the tokamak concept in a broad-based fusion energy program?** This paper examines the motives for pursuing alternate concepts, the steps involved and costs of alternate concept research, and the current status and process of alternate concept research as conducted in the U.S. fusion energy program. Note that this paper does not assess the likely attractiveness of any alternate fusion concept, nor does it suggest the appropriate level of effort to be devoted to it. Rather, the paper reviews the level of development, which may not be closely related to the long-term potential of a concept.

There are critical issues for the U.S. fusion energy program that are beyond the scope of this background paper. Three of the most important are noted here. First, **this paper does not examine the rationale for the overall fusion energy program. In particular, the role of the fusion energy program in meeting long-term energy needs and the level of research effort justified by that potential role are critical issues for the program.** Whether or when fusion will meet the goal of becoming an economically and environmentally attractive energy option will depend on more than just success in a continuing multidecade R&D program. It will also depend on the pace of progress in the other energy technologies

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[2] U.S. Congress, Office of Technology Assessment, *Starpower: The U.S. and the International Quest for Fusion Energy,* OTA-E-338 (Washington, DC: U.S. Government Printing Office, October 1987).

[3] Renamed the House Committee on Science.

with which fusion must eventually compete. These energy technologies span a broad array, from advanced nuclear fission reactors to renewables such as biomass, wind, and photovoltaics to improved methods for finding, extracting, and burning fossil fuels including coal, natural gas, and oil. Substantial improvements in energy efficiency technologies continue as well.[4] To the extent that these energy technologies continue to improve, they present an increasingly challenging market environment for future fusion powerplants. While progress in fusion is continuing, other energy technologies are improving as well, often with some federal support. The tradeoffs in timing and choice of R&D efforts in competing energy technologies including fusion are critical issues for fusion research policy beyond the scope of this paper.[5]

A second and related critical issue for the fusion energy program not addressed in this paper has to do with the possibility of declining budgets. **Proposals to greatly reduce fusion energy research spending heighten the importance of identifying possible new roles, directions, and goals for the program under scenarios of flat or declining budgets.** This paper discusses the likely cost involved in continuing along the current path of fusion research, and it is substantial. As noted below, the current fusion energy program goals and directions, including construction and operation of large new tokamaks, are inconsistent even with flat budgets; the possibility of declining budgets sharpens the issue. Certainly, potentially valuable work can be performed under a wide range of research budgets. However, this would call for revised goals and directions. For example, even under substantial cuts, some see the possibility of sustaining progress by focusing on physics issues using existing machines, increasing international collaboration, supporting a modest but expanded effort to investigate alternate concepts, and concentrating on materials and technology advances that would be necessary for fusion powerplants.

An effort to identify the most productive uses of fusion energy funds under a variety of scenarios could provide information critical in making budget decisions. Eventually, however, absent novel, unexpected science developments, progress toward development of a fusion powerplant would require a commitment to construction of expensive new facilities. Finally, under any budget scenario, consideration must be given to existing commitments such as decommissioning TFTR and the international agreement to complete the engineering design of ITER. These two commitments alone total a few hundred million dollars over the next several years.

A third critical issue for the U.S. fusion energy program that is beyond the scope of this background paper has to do with the increasing internationalization of research.[6] Due to the very high estimated cost of some fusion facilities, the domestic fusion energy program is pursuing cost-sharing collaborative efforts with several countries. ITER, with a roughly estimated design and construction cost on the order of $10 billion, is the leading example (see box 1-1). The institutional structure for this type of international col-

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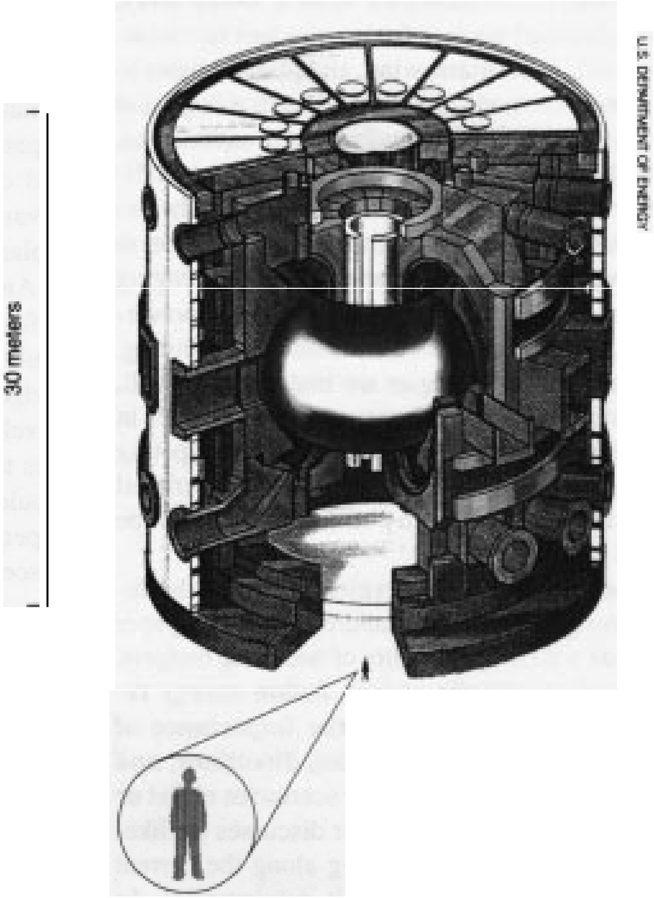
[4] See, e.g., the following reports by U.S. Congress, Office of Technology Assessment: *Energy Efficiency: Challenges and Opportunities for Electric Utilities,* OTA-E-561 (Washington, DC: U.S. Government Printing Office, September 1993); *Industrial Energy Efficiency,* OTA-E-560 (August 1993); *Building Energy Efficiency,* OTA-E-518 (May 1992); *Energy Efficiency in Federal Facilities: Government by Good Example?* OTA-E-492 (May 1991).

[5] See U.S. Congress, Office of Technology Assessment, *Energy Technology Choices,* OTA-E-493 (Washington, DC: U.S. Government Printing Office, July 1991). The Secretary of Energy recently commissioned a review of DOE civilian energy R&D programs that will address this issue at some level. See The Honorable Hazel R. O'Leary, Secretary of Energy, letter to George M. Scalise, Sept. 8, 1994. Also, the President's Council of Advisors on Science and Technology will report on the fusion energy program in Summer 1995.

[6] OTA is currently examining the role of international collaboration in large science projects. That effort, due for completion in summer 1995, will examine the increasingly international character of several scientific fields, including that of fusion energy research.

BOX 1-1: The International Thermonuclear Experimental Reactor

The United States, the European Union, Japan, and the Russian Federation are engaged in an unprecedented collaboration on the engineering design of the proposed International Thermonuclear Experimental Reactor (ITER). This collaboration has its roots in discussions among the leaders of the European Community, Japan, the Soviet Union, and the United States in the mid-1980s. ITER's purpose is to establish the scientific and technological feasibility of magnetic fusion energy as a source of electric power by demonstrating controlled ignition and extended burn of deuterium-tritium plasmas and to demonstrate and test technologies, materials, and nuclear components essential to development of fusion energy for practical purposes. It would not be capable, however, of actually generating electricity. Demonstrating the production of electricity in a magnetic fusion energy powerplant would be left to the DEMO reactor, a device anticipated for construction no sooner than 2025.



U.S. DEPARTMENT OF ENERGY

The proposed International Thermonuclear Experimental Reactor.

If built, ITER would be by far the largest, most capable, and costliest fusion experiment in the world. ITER uses a tokamak design, and would stand over eight stories tall and 30 meters in diameter. The device is intended to sustain controlled fusion reactions in a pulsed mode for periods of up to 15 minutes. ITER is expected to be capable of producing over 1,000 megawatts of thermal fusion power. Temperatures inside the confinement chamber would be up to 1,000 degrees centigrade, and maintenance and monitoring of the radioactive containment will have to be carried out by remote methods. The impressive scale of ITER is dictated by the physical requirements of heating and containing a plasma to fusion conditions on a steady state basis using available technology and materials. ITER offers not only great scientific challenges, but practical technological challenges as well. For example, ITER's superconducting magnetic coils will be the largest ever manufactured. Each coil will weigh over 400 tons. The amount of superconducting materials required to make them exceeds the available manufacturing capabilities of any one party, therefore a cooperative effort is underway to coordinate the materials manufacture, fabrication, and assembly.

ITER is being conducted in four phases under formal intergovernmental agreements among the parties, These are: 1) the now-completed conceptual design activities (CDA); 2) the engineering design activities (EDA); 3) the construction phase; and 4) the operations phase. Each phase is to be governed

BOX 1-1 (cont'd.): The International Thermonuclear Experimental Reactor

by a separate agreement among the parties and costs are shared equally. The first phase of the ITER project, CDA, was carried out from January 1988 to December 1990. All four parties contributed personnel and support to the ITER team for development of a conceptual design, scope, and mission for the project.

Currently, ITER is in the EDA phase, which is scheduled to continue until July 1998. Under the ITER Agreements, each of the parties has committed the equivalent of $300 million (1993 dollars) worth of personnel and equipment to the design effort. The purpose of the ITER EDA phase is to produce a "detailed, complete, and fully integrated engineering design of ITER and all technical data necessary for future decisions on the construction of ITER." On completion, the design and technical data will be available for each of the parties to use either as part of an international collaborative program or in its own domestic program. Other objectives of the EDA phase are to conduct validating R&D supporting the engineering design of ITER, to establish siting requirements, to perform environmental and safety analyses related to the site, and to establish a program for ITER operation and decommissioning.

EDA activities are overseen by an ITER Council composed of two representatives of each party. Decisions by the Council are based on consensus. Under the Council, the ITER Director is responsible for coordinating the activities of the Joint Central Team—an international design team composed of scientists, engineers, and other professionals assigned to the ITER project by the parties. The Joint Central Team activities are carried out at three Joint Work Sites—Garching, Germany; Naka, Japan; and San Diego, California. Each work site team is responsible for a different aspect of ITER design. The work of the Joint Central Team is supported by R&D activities by the "home country" fusion programs. Tasks are assigned and coordinated by the ITER Director in consultation with the ITER Council, the Joint Central Team, and each party's designated "Home Team" Leader.

The next major step in the ITER process will be the negotiation of a process for deciding on a host site for ITER. Exploratory discussions on a site selection process are currently underway. Site selection will have to be accomplished so that the EDA team can complete specific site-related safety, environmental and economic analyses, and design work for the ITER facility. Following site selection, a decision on whether to proceed to ITER construction and operations phases is scheduled to be made before 1998 and would require a new international agreement.

The ITER construction phase is tentatively planned to start in 1998 and to be completed by 2005. Initial estimates of ITER construction cost had been $6.9 billion in July 1993 dollars; some analysts have projected ITER costs of between $8 billion to $10 billion. Detailed cost estimates for this one-of-a kind research facility await completion of ITER engineering design work. Interim design and cost analyses are expected in mid-1995. Final design and cost estimates are due in January 1998, assuming site selection has been completed.

The fourth or operating phase of ITER is proposed to begin in 2005 and run through approximately 2025. The early phases of ITER operation would be dominated by a focus on the physics issues relating to achieving and sustaining an ignited plasma. A more intense engineering phase will follow. As an engineering test facility, researchers would be able to install, test, and remove numerous ITER components, experimental packages, and test modules to test materials properties, component characteristics, performance, and lifetimes in an environment approximating the conditions of an operating fusion powerplant. This experience would aid efforts at design and development of a demonstration fusion powerplant.

laboration in the construction and operation of large facilities remains to be developed, and its ultimate success will require dedication, flexibility, and innovation. This paper does examine one current case in the coordination of the domestic fusion energy program in the increasingly international fusion arena—the methods by which TPX is coordinated with ITER, and the potential contribution of TPX to that much more ambitious facility. It does not, however, examine the methods by which ITER can be successfully developed, nor does it evaluate key issues in the ITER program as it relates to the broader fusion energy development effort, such as project scope and timing. Further, it does not examine how the overall U.S. fusion energy program, including alternate concepts research, could be more fully integrated into the world effort.

ACHIEVEMENTS AND CHALLENGES OF THE U.S. FUSION ENERGY PROGRAM

Fusion reactions, which power our sun and the stars, occur when the nuclei of two lightweight atoms (e.g., isotopes of hydrogen such as deuterium and tritium) combine together, or fuse, releasing energy (see figure 1-1). Understanding and controlling the conditions that allow practical fusion to occur on earth, such as temperatures of about 100 million degrees Celsius, present great scientific and technical challenges. At such high temperatures, matter exists as plasma (a state in which atoms are broken down into electrons and nuclei) that cannot be contained by any solid container.

Primary responsibility for fusion energy development rests with DOE and its Office of Energy Research. Most effort in fusion energy research has been devoted to the magnetic confinement approach, which uses magnetic fields to control the range of motion of the plasma. Several different magnetic fusion energy (MFE) confinement concepts have been investigated, the most advanced of which is the tokamak reactor. Considerable effort has also been devoted to inertial confinement, in which a pellet of fusion fuel would be heated and compressed by intense lasers or ion drivers to such high densities that the fuel's own inertia is sufficient to contain it for the very short time needed for fusion to occur. Inertial confinement fusion research mimics, on a very much smaller scale, processes in the hydrogen bomb, and to date, much of the research relevant to inertial fusion energy (IFE) has been performed by DOE's Office of Defense Programs for its applications to nuclear weapons physics and stockpile stewardship responsibilities.

The ultimate goal of DOE's fusion energy program is "to demonstrate that fusion energy is a technically and economically viable energy source." DOE's primary emphasis in fusion energy is on developing the tokamak, and devotes by far the largest share of the current fusion energy budget to support design of two planned tokamak reactors. Of the $373 million requested budget for fiscal year 1995, 41 percent was for direct and indirect design and support of ITER, and 33 percent was intended for design, construction, and support of TPX.[7] Another 14 percent was to support operations of the largest operating U.S. tokamak, TFTR. The remainder of the fusion energy budget is devoted to such diverse activities as advanced materials development, fusion technology development, and study of alternate concepts including IFE. In addition, in fiscal year 1995 the Office of Defense Programs devoted $176 million to inertial confinement fusion research, much of which is relevant to IFE.

Much progress has been made in fusion energy research over the past few years, but far more remains to be done. Most notably, recent experiments at TFTR attained a record in fusion energy production of 10.7 megawatts (MW),

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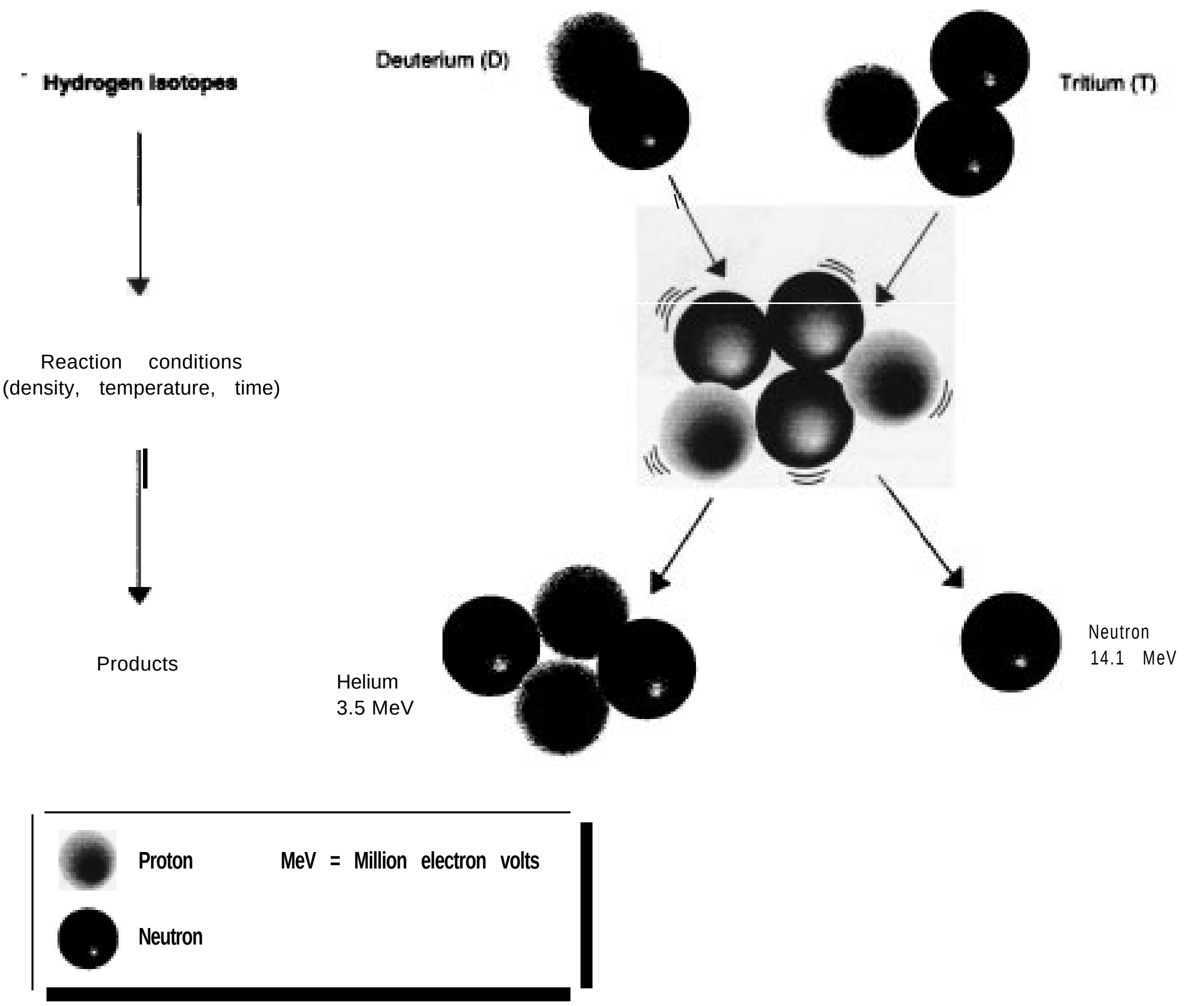
[7] U.S. Department of Energy, "Fusion Energy Program," briefing package presented by N. Anne Davies to Office of Technology Assessment staff, Apr. 28, 1994. Note that of the $152 million related to ITER, $81 million was for a diverse array of "support" activities rather than direct ITER design and R&D work. Similarly, of the $118 million related to TPX, $56 million was for support.

FIGURE 1-1: A Deuterium-Tritium Fusion Reaction



SOURCE: Office of Technology Assessment 1995, based on figure from U.S. Department of Energy, Office of Fusion Energy.

amounting to a factor of about 100 million increase in fusion power production over 20 years of research. However, even the tokamak, the most advanced fusion energy concept, faces scientific and engineering challenges. Scientific challenges remaining to be met for MFE include achieving *high energy gain* (energy output that is many times higher than energy input to create the reactions) and *ignition* (the point at which a reaction is self-sustaining even when external heating is turned off) in a *steady state* (continuous, rather than intermittent, operation).[8] However, even *breakeven* (the Point at which the energy produced

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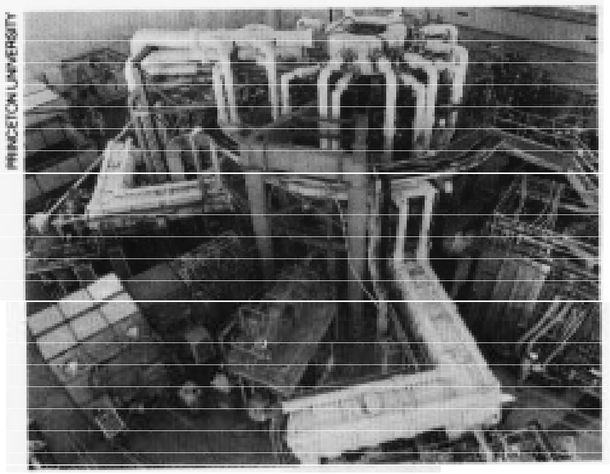
[8] Fusion scientists typically have defined scientific feasibility as attainment of high energy gainer ignition. Steady state operation is generally not included in definitions of scientific feasibility, although it presents an important scientific challenge that must be met by any MFE powerplant.


PRINCETON UNIVERSITY

The Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory set world records for fusion reactions using dueterium-tritium fuel in 1993 and 1994. TFTR, the largest U.S. tokamak, is scheduled to be shut down in 1995.

by fusion reactions equals the energy input to heat the plasma[9]) has remained beyond the reach of current facilities.[10] The highly successful TFTR experiments of the past year, for example, reached just over one-quarter of breakeven--about 40 MW of external power were introduced to the plasma to create about 10.7 MW in fusion reactions. This fusion energy production lasted for only a few moments. If constructed, ITER would be the first MFE device expected to achieve ignition, and to operate for long pulses of several hundred to over one thousand seconds.

Developing a commercial prototype fusion powerplant requires more than merely meeting scientific challenges. It further requires meeting a series of engineering challenges, including development of materials, components, and systems for operating fusion reactors. According to DOE, the main scientific and technological issues for the MFE effort are the following:

1. ignition physics (e.g., understanding the properties of a self-sustaining fusion reaction);
2. magnetic confinement configuration optimization (i.e., determining how best to shape the magnetic fields confining the plasma);
3. fusion nuclear technology (engineering systems to fuel, maintain, and recover energy from a fusion reactor); and
4. low activation materials development (development of materials that will not become highly radioactive in a fusion reactor).

Meeting these challenges, by their very nature, requires abroad-based program of scientific, technical, and industrial R&D.

Under plans established a few years ago, **tens of billions of dollars and about three decades of continued successful R&D will be needed before the science and technology are sufficiently advanced to enable construction of DEMO following ITER, and a subsequent commercial prototype may be operational only by around 2040.** It is worth noting that fusion researchers have long suggested a three-decade horizon for development of fusion energy. As budgets have not met the expectations of researchers, and as the science has proven challenging, the horizons have continued to recede.

Congress will **face tough decisions about budget priorities for the fusion energy program over the next few years, as current plans for pursuing the tokamak imply a doubling or more from fiscal year 1995's funding of $373 million (see figure 2-8**in chapter 2). The budget increase has not been explicitly stated in previous

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[9] Note that the amount of power consumed in heating the plasma is only part of the power actually consumed by the entire experiment. Losses incurred in generating the heating power and delivering it to the plasma are not included, nor is the power needed to operate systems such as the magnets and the vacuum system.

[10] In discussing results of scientific experiments, fusion scientists often use the term "equivalent plasma conditions." This term refers to the development of a plasma not composed of fusion fuel (e.g., a mixture of deuterium and tritium, D-T) but rather of a plasma that is easier to work with (e.g., deuterium alone). While fusion reactions can occur in the deuterium-only plasma, far less energy is produced than with D-T. Thus, equivalent breakeven conditions refers to temperatures, densities, and confinement times in a plasma that would have resulted in true breakeven had such conditions been attained with fusion fuel. Using this definition, Europe's large tokamak, JET, has achieved the breakeven level in an equivalent deuterium plasma.

DOE budget submissions, but is implied by new facilities identified by DOE and continuation of the base program. Fusion researchers have long identified the need for substantially larger research budgets, but congressional priorities have varied with changing energy markets and other factors, leading often to uncertain and fluctuating budget prospects. For example, the Secretary of Energy's Fusion Policy Advisory Committee indicated in 1990 that the fusion energy budget would need to be increased to about $700 million annually in fiscal year 1990 dollars (not including the Defense Programs research in inertial confinement fusion) to meet program goals, but the budget since then has been at only about one-half that level (see figure 2-1 in chapter 2).

By far the greatest single budgetary requirement for the fusion energy program over the next decade will come from ITER, if current plans are pursued. No decision has been made by the ITER partners on whether to proceed beyond engineering design and to actually build the device. However, if ITER is pursued according to the current proposed schedule, the U.S. contribution to construction alone could require nearly a doubling of the current total fusion energy program budget over the next few years. For example, although construction costs remain uncertain, assuming the United States bears a one-quarter share to build an approximately $10 billion ITER over an eight-year construction horizon implies an average ITER construction budget alone that is over $300 million annually, or over 80 percent of the entire current U.S. fusion energy program budget. Unless the budget is greatly increased, it will not be possible to complete the ITER project as currently envisioned.

Finally, the information and analyses needed to support congressional decisions on fusion energy budgets and policy are not readily available. **Despite congressional requirements in the Energy Policy Act of 1992, as of December 1994, DOE has not issued a strategic management plan for the fusion energy program by which the program's progress can be judged.** The management plan was required to be prepared by April 1993 and progress reports on meeting the plan milestones were to be updated biennially. The plan is to include specific program objectives, milestones, schedules, and cost estimates for technology development, program management resource requirements, and an evaluation of international fusion programs.

Undoubtedly one of the greatest challenges to developing the strategic management plan is the need to address the longstanding divide between the expected budgetary requirements of the fusion energy program and the history of funding at substantially lower levels. Because pressures to contain and reduce overall federal spending are likely to continue, the budgets needed to carry out the fusion energy program as currently envisioned may not be realized. **Without substantial funding increases, the program will have to change significantly from the current direction and new goals will be have to be set.**

FINDINGS ON TPX

TPX is intended to provide scientific and technical advances that are clearly necessary to the ultimate realization of a tokamak powerplant. With regard to scientific issues, TPX is designed to demonstrate and operate at long-pulse or near-steady state conditions, essential for an eventual powerplant. TPX is also designed to explore advanced operating modes or regimes that, if successful, would allow increases in confinement efficiency and power density in future tokamaks, and ultimately reduce the size and cost of a tokamak fusion energy reactor. With regard to technological advances, TPX would be the first large fully superconducting tokamak (i.e., the magnets will be superconducting, greatly reducing the amount of electrical power they consume). This would be a substantial achievement, and is essential for steady-state operation of an MFE powerplant. TPX would also allow investigation of a variety of configurations for the divertor, a major component essential in any eventual tokamak energy powerplant for removing both reaction products (e.g., helium "ash" produced by fusion) and heat. Remote handling, necessary for maintenance in a radioactive environment created by fusion reactions, would also be developed for maintenance of mildly radioactive equipment where limited human intervention will still be possible.

TPX is also intended to maintain the strength of the U.S. magnetic fusion energy program after TFTR retires in 1995. There are several other U.S. tokamaks operating currently, the largest of which are the DIII-D at General Atomics in San Diego and Alcator C-Mod at the Massachusetts Institute of Technology. However, absent TPX, there will be no new U.S. tokamak under development. To support a strong MFE research and development capability, TPX has been organized as a national facility with design and operation guided by members from various universities, national laboratories, and U.S. industries. Proponents note that experience with building major TPX systems such as the superconducting magnets could give U.S. industry a firmer base in competing to construct ITER. They also note that both Japan and Europe have large tokamaks that can continue operations for several years beyond the retirement of the U.S.' TFTR, supporting their base tokamak programs until the next steps are decided for ITER. Note, however, that TPX would not be operational before the year 2000, and so could provide design and construction benefits but not experimental benefits before them.

TPX is not scheduled to provide any unique scientific and technological advances essential to ITER. Indeed, when the ITER conceptual design activity was completed in 1991, DOE had no formal plans to build TPX or a device like it, although a steady-state advanced tokamak was recommended by the Fusion Policy Advisory Committee as one of four major facilities needed prior to the construction of a demonstration fusion reactor. Also, under current plans, TPX will become operational only after the start of ITER construction, greatly reducing the ability to transfer TPX experimental results to ITER design. No other partner in the ITER project has found it essential to pursue a device with TPX's capabilities as part of the program for successful development of ITER.[11] The ITER design group indicates that it intends to provide the flexibility in ITER to examine most of the technology and science areas to be examined by TPX. The ITER interim design, expected in June 1995, should allow a better assessment of whether this is indeed the case.

One area in which TPX may produce unique scientific benefits concerns the investigations of specific steady-state, advanced operating modes. Currently, ITER is being designed with more conservative operating modes than TPX. However, the ITER design group has indicated its intent to maintain the flexibility to examine a range of advanced modes approaching those of TPX in the later phases of its experimental effort. Building in this flexibility may be expensive, though, as significant upgrades to auxiliary systems may be required. Again, the ITER interim design should allow a better assessment of the degree of flexibility and its costs. Whatever the extent of flexibility built into ITER, TPX could provide unique benefits. To the extent that ITER's flexibility is limited, TPX could play an important scientific role in examining the advanced operating mode issue. On the other hand, even if wide flexibility would be built into the ITER design, TPX results may help identify certain unpromising approaches and thereby help avoid performing unpromising retrofits or upgrades to ITER. This could be important since testing in ITER of some advanced operating modes examined in TPX could require a potentially costly reconfiguration of ITER.

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[11] The Japanese have also carried out a conceptual design of a superconducting machine called the JT-60 Super Upgrade (JT-60SU). It would have many of the features planned for TPX and would be larger and more powerful. However, construction has not been approved, and is not expected prior to decisions about siting and construction of ITER. Note also that both Europe and Japan currently have large, relatively young tokamaks that will continue to provide a major focus for their own programs for several years. In contrast, the largest U.S. tokamak, TFTR, is scheduled to retire in 1995.

TPX's primary expected contribution to ITER would be the ability to perform experiments on a device that is smaller, more flexible, and less costly to operate. Because of the scheduling overlap between the projects, it will be impossible to take full advantage of the potential TPX results in the design and construction of ITER. For example, as noted above, some potentially costly decisions to build flexibility into ITER design allowing examination of advanced operating modes will be made long before TPX experimental results would be available. There may be some construction benefits as, for example, industrial experience gained from TPX construction may be useful preparation for ITER construction.

A more important potential benefit concerns decisions on possibly costly retrofits to ITER to examine advanced operating modes, as discussed above. There are other potentially important benefits in the area of ITER operations. For example, TPX experiments in long-pulse operation may shorten the needed schedule for such experiments at ITER, allowing ITER to move more quickly into research areas for which it is uniquely suited. The cost and schedule savings could be substantial, given ITER's likely high operating costs and lower flexibility relative to TPX. For example, annual operating costs for ITER, while still undetermined and highly uncertain, may be on the order of several hundred million dollars. However, the likely acceleration in the ITER operating schedule enabled by TPX remains speculative. Overall, **while the potential benefits of TPX to ITER can be real, their magnitude is uncertain, and DOE has not estimated their value. Further, there are no plans to account for the benefits of TPX to ITER as part of the direct contribution to the U.S. commitment to ITER.**[12]

Unless tested in ITER, there will likely be considerable uncertainty of the transferability of TPX results to DEMO. There is no question that successful achievement of many of the goals to be investigated by TPX—steady-state operation, superconducting magnets, remote handling, and advanced divertor design in particular—will be necessary if a tokamak-based fusion power reactor is to become a reality. These areas can be incorporated in ITER from the start or be integrated into it after testing in TPX or elsewhere. Integration of advanced tokamak operations results into ITER, however, may be more limited and require significant upgrades. Since successful demonstration of these operations can have significant consequences for the economics of a fusion power reactor using the tokamak concept, it will be important to build them into the DEMO design. To the degree that advanced regime operation will not have been tested in a long-pulse ignited device, a difficult decision will eventually be needed to balance the scientific risk of incorporating that feature in an expensive facility such as DEMO against the benefits of smaller size and lower cost.

The value of TPX to the magnetic fusion energy program could increase if ITER is delayed. The physics and technology TPX would investigate are fundamental for the development of any tokamak powerplant, but the prospects for success are by no means certain. However, incorporating the results of the TPX advanced operating mode experiments in the design of ITER would require a several-year delay of ITER design and construction. While many of the steady-state and advanced operating regime issues to be investigated by TPX are unique to the tokamak concept, the results of technology development could also be useful to other MFE concepts. For example, operation of superconducting magnets, divertors, and remote handling will be necessary on any eventual MFE reactor.

Overall, TPX is a costly undertaking that continues to receive considerable congressional attention. However, it presents only the most im-

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[12] This is consistent with the policy of the ITER partners that physics research performed by the partners in support of ITER is not counted against commitments to ITER design and construction.

mediate example of a series of difficult decisions that Congress and DOE will have to make about the fusion energy program. Its budget of about $2 billion including construction and operation over the next 15 years[13] represents only about 5 to 10 percent of the likely total U.S. MFE research budget needed to enable a commercial prototype tokamak powerplant by the year 2040. **Regardless of decisions on TPX, the overall tokamak fusion energy effort will require justifying a series of expensive research activities, of which the U.S. contribution to ITER presents the largest single budgetary requirement in the near future.**

FINDINGS ON ALTERNATE CONCEPTS FOR FUSION ENERGY

Over the past several decades, the tokamak has clearly emerged as the most scientifically successful MFE concept with unmatched plasma temperatures, densities, and confinement times. It is the focus of U.S. and world fusion energy programs. There are, however, a number of alternate fusion concepts[14] for which the knowledge base is more limited (as shown in table 4-1 in chapter 4). These include several non-tokamak MFE concepts, some of which have been extensively pursued—such as the stellarator, a close variation of the tokamak.[15] Several other MFE concepts including mirrors, reversed field pinch, and the field reversed configuration have been examined less thoroughly. Scientific exploration of IFE concepts has been extensively pursued primarily for reasons related to nuclear weapons. However, the total research effort devoted to inertial fusion, including both defense and civilian programs, makes IFE the largest alternate approach to fusion in the United States. A number of more novel fusion energy concepts have been suggested that take fundamentally different, and more speculative, approaches including muon catalysis, electrostatic confinement, and colliding beams.

Over the past several years, the fusion energy program was substantially narrowed to focus on the tokamak primarily for budgetary rather than technical reasons. This narrowing was partly a response to congressional pressure.[16] As noted by DOE in its fiscal year 1993 budget request:

> . . . [F]iscal constraints have required the program to prematurely narrow its focus to the tokamak concept, including tokamak improvement activities, and to eliminate major alternate magnetic confinement program elements.

Operation of several existing experimental devices was halted or minimized. In one example, construction of the LSX, a $14-million device to test the field reversed configuration, was completed in 1990 followed by encouraging startup tests, but funding to continue confinement experiments was not available. In another example, construction of a 75-percent-complete, $75-million device to test another promising concept, the reversed field pinch, was canceled in 1990. Similarly, in fiscal year 1994, the civilian IFE budget was reduced by 50 percent to $4 million, well be-

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[13] The total construction cost of TPX, estimated to be $694 million in as-spent dollars, was planned to be spent by fiscal year 2000, with a peak of about $130 million to $140 million each in fiscal years 1996 to 1998. However, while Congress appropriated funds in fiscal year 1995 for acquisition of major TPX systems, it restricted funds to begin construction. As of December 1994, DOE had not identified the impact of the restriction on the overall cost and schedule of TPX. DOE projects annual operating costs of about $150 million in fiscal year 2000 dollars for the 10-year life of the facility once operations begin.

[14] In this report, the term “alternate concept” has the meaning “nontokamak concept.”

[15] Japan is currently completing the construction of a stellarator, the Large Helical Device, at a total cost of about $1 billion. Germany is pursuing a stellarator of similar size and cost.

[16] See, e.g., “Conference Report on the Energy and Water Development Appropriations,” H. Rept, 103-292, *Congressional Record* 139:H7906, at p. H7948, Oct. 14, 1993 (daily ed.).

low the level needed to continue work developing a planned heavy ion driver device despite successful operations on a smaller test facility.[17]

There were, of course, technical reasons that the tokamak was retained as the primary focus—none of the alternate MFE concepts had attained similar performance, and a variety of technical challenges and uncertainties remained. However, **there is a widely held view that the narrowing of the fusion energy program was premature and did not reflect the benefits of pursuing alternate concepts.** The view that examination of alternate fusion confinement concepts is an important component of a fusion energy program is held even by many supporters of the tokamak, including DOE. There are clear reasons for supporting an alternate concepts program as part of the fusion energy program. Among them is that **pursuit of promising alternate concepts, including novel ones, may provide a fusion energy option should the tokamak prove technically infeasible or commercially unattractive.** It is important to note, however, that in many cases the knowledge base is not adequately developed to determine whether some alternate concept is likely to exceed the performance of the tokamak. **Data and theory do not currently support large-scale experimentation for any alternate MFE concept other than the stellarator.**

The necessary dependence on experimental facilities and research to verify theory can make fusion energy concept development expensive. **DOE suggests that a "healthy, but constrained" alternate concepts program would require about $100 million per year.** This effort would include construction and operation of some intermediate-scale facilities. **However, a substantial amount of information that provides a firmer basis for making future alternate concept decisions could be developed with a far more modest program.** For example, some fusion researchers have proposed a broad-based theoretical study of a wide range of alternate concepts that could be performed for less than 1 percent of the fusion energy program budget. This could help in identifying attractive prospects for additional development efforts, or for discarding some concepts as not showing substantial promise as the most attractive fusion energy device. While each alternate concept has its own development profile, next steps need not necessarily cost a substantial fraction of the fusion energy program budget. For example, experiments on existing reversed field pinch and field reversed configuration devices could be resumed and increased for under $5 million dollars, providing considerable insight into the prospects for these promising but still speculative concepts. Also, next steps on intermediate-scale facilities need not necessarily be conducted by the United States alone, but might be undertaken through collaborative international efforts.

IFE using a heavy ion driver is widely considered the primary alternate concept, and involves the costliest next steps. However, **proponents suggest a development path for the heavy ion driver IFE concept leading to a demonstration powerplant that could be substantially more flexible and less costly than that planned for the tokamak development effort.** There is considerable scientific and technical uncertainty with IFE, and development costs are uncertain as well. Overall, some IFE proponents envision a $4-billion civilian effort (with another $4 billion from defense programs) spread over a number of moderate-cost facilities resulting in a demonstration powerplant. In contrast, design, construction, and operation of ITER alone is expected to cost well in excess of that amount, and is only one of the major future research activities involved in the tokamak development program. There remain considerable scientific and technical challenges with heavy ion IFE, however, and the estimated cost of the effort

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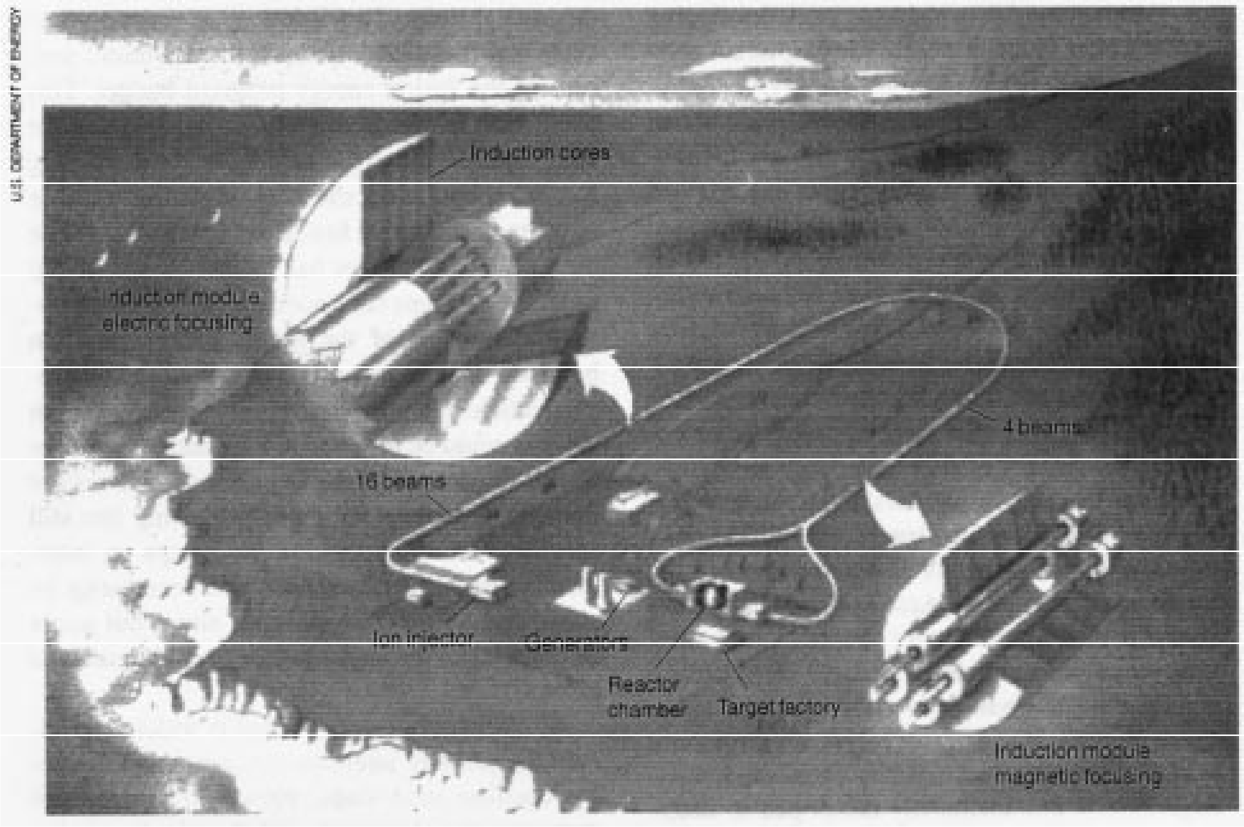
[17] The budget for the DOE Defense Program inertial confinement fusion program, which performs much of the research relevant to IFE, was not affected.



A conceptual inertial fusion energy powerplant using a heavy-ion induction linear accelerator.

could rise significantly as more experience is gained.

One critical issue with IFE is its relationship to the considerably larger inertial fusion program now included within the nation's nuclear weapons programs. This relationship provides an advantage for the IFE effort, in that much of the funding for basic scientific research needed has come under DOE's defense program. The next major step in IFE development is to explore ignition physics, a topic also relevant to maintaining nuclear weapons expertise. The IFE development plans assume completion of the National Ignition Facility (NIF), a proposed $1-billion research facility being considered under the Defense Program at DOE as part of the stockpile stewardship program to maintain expertise in nuclear weapons physics. Whether NIF is constructed will probably depend more on weapons-related reasons, including its role in maintaining nuclear weapons design expertise and the potential effects on weapons proliferation, and budget considerations rather than its benefits for the fusion energy program.[18]

In summary, while alternate concepts provide no panacea for fusion energy development, there is merit in examining them as part of a broad fusion program Relative to the expected costs of the tokamak effort, a great deal of exploratory work can be conducted at modest cost. Assuming some of the concepts prove technically promising, however, further development

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[18] In October 1994, the Secretary of Energy approved NIF for engineering design (Key Decision 1,or KD-1). The primary mission of NIF is to demonstrate inertial fusion ignition and modest energy gain.

may require larger budgets for construction of expensive facilities. As with the tokamak effort, the potential role of the overall fusion energy program in meeting long-term energy needs, and the level of research effort justified by that potential role, are critical issues for the direction of alternate concepts research.