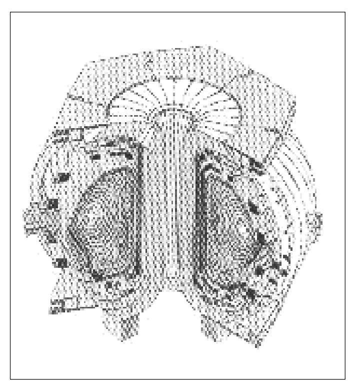
The Tokamak Physics Experiment 3

In the fiscal year 1993 budget request to Congress, the U.S. Department of Energy (DOE) asked for $20 million for "conceptual design and R&D" for a tokamak physics experiment (TPX) "to address the physics of tokamak improvements."[1] This request was the culmination of an effort started in 1991 by DOE, in the wake of the cancellation of the Burning Plasma Experiment (BPX), to come up with a new experimental device to follow the completion of work on the Tokamak Fusion Test Reactor (TFTR). If completed, TPX would be the first large experimental magnetic fusion device built and operated in the United States since TFTR operation began in 1982. The principal focus of TPX is to examine a range of physics and engineering issues whose successful resolution could greatly reduce the cost and complexity of a commercial fusion powerplant based on the tokamak concept.[2] In addition, TPX is intended to support design and operation of the International Thermonuclear Experimental Reactor (ITER).

The principal features of TPX are to be its ability to explore advanced operating regimes that could substantially improve tokamak powerplant performance, and to operate at near steady-state conditions with a design plasma pulse length of 1,000 seconds.[3] TPX is to be built at the Princeton Plasma Physics Laboratory in the area currently occupied by TFTR. The most recent estimate of



[1] U.S. Department of Energy, *FY1993 Congressional Budget Request*, DOE/CR-0006 (Washington, DC: January 1992), vol. 2, p. 390.

[2] U.S. Department of Energy, *Tokamak Physics Experiment*, UCRL-TB-114199 (Washington, DC: March 1993).

[3] Ibid.

total project cost—construction plus associated operations during construction—is $694 million.[4] If TPX construction starts by the end of 1995, completion is expected in 2001. Once completed, operating costs are expected to be $150 million per year for the project's 10-year lifetime.[5]

This chapter presents an analysis of the TPX project. The chapter starts with a description of the process leading up to the TPX decision. Next, a description of the machine is given including its scientific and technical goals. Several of the issues about TPX emerge from this analysis.

HISTORY OF THE TPX DECISION

The roots of TPX lie in the 1990 report of the Fusion Policy Advisory Committee (FPAC) to DOE.[6] That report set forth a series of recommendations to guide the future of the U.S. fusion energy program. The committee recommended that the United States "commit to fusion as a potential energy source," that the program should be directed toward energy production, and that it should set as a specific goal the construction of a demonstration powerplant (DEMO) by 2025.[7] The committee also recommended that to achieve these goals, DOE needed to start four new facilities in the 1990s including: a burning plasma experiment, ITER, a steady-state advanced tokamak, and a neutron source for materials development. These facilities would be necessary to investigate a series of important scientific and technical issues that needed resolution if magnetic fusion energy was to become a reality.

At the time of the FPAC report, DOE was proceeding with conceptual design of BPX and was a partner with Japan, the European Union, and Russia in the conceptual design activity of ITER. BPX was to be a moderately sized tokamak with very high magnetic fields. It was to be capable of achieving ignition (reaching the point where the fusion reaction becomes self-sustaining) for the purpose of investigating the properties of burning (self-heated) plasmas,[8] particularly behavior of a plasma dominated by alpha particle heating.[9] Such heating is expected to be the principal source of heating in a deuterium and tritium (D-T) fusion plasma once ignition is achieved. These results were expected to provide "valuable" input to ITER and ultimately, along with ITER, to be essential to reaching a DEMO by 2025. While BPX was expected to achieve a large net energy gain, it was not being designed for steady-state operation. That task was to be left to other, unspecified experiments, although the FPAC report did rec-

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[4] This cost estimate was made prior to DOE's submission of its fiscal year 1995 budget request. Since Congress did not grant approval for DOE to begin construction of TPX in fiscal year 1995, the cost estimate will probably increase.

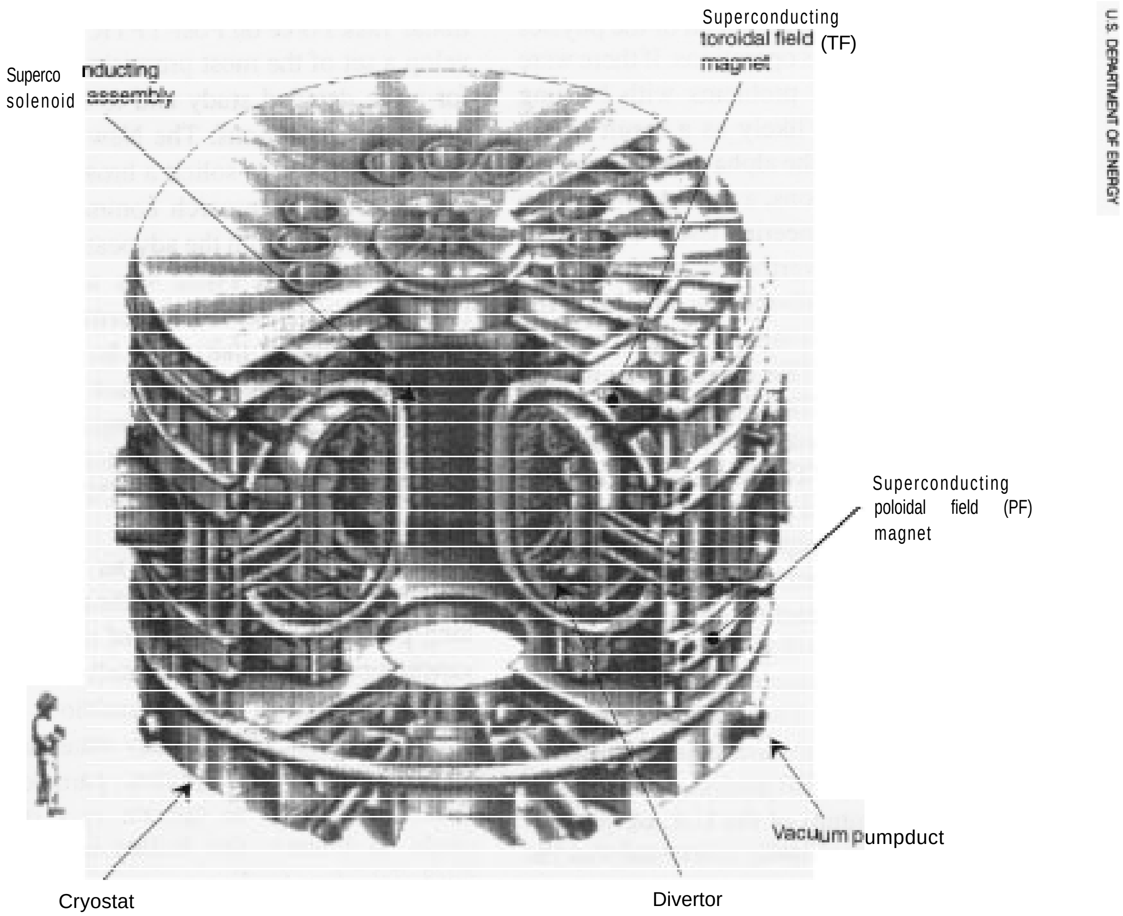
[5] U.S. Department of Energy, *FY1995 Congressional Budget Request: Project Data Sheets,* DOE/CR-0026 (Washington, DC: February 1994), vol. 2., p. 90.

[6] U.S. Department of Energy, *Final Report, Fusion Policy Advisory Committee (FPAC),* DOE/S-0081 (Washington, DC: September 1990).

[7] Ibid., p. 3.

[8] U.S. Department of Energy, *FY1988 Congressional Budget Request,* DOE/MA-0274 (Washington, DC: January 1987), vol. 2, p. 327.

[9] One of the products of the fusion reaction between deuterium and tritium is the helium-4 nucleus, an alpha particle. These alpha particles, in turn, possess energy from the fusion reaction. The alpha particles are also subject to confinement by the external magnetic field, although they eventually diffuse out of the fusion plasma. While confined, the alpha particles can give up their energy by collisions with the deuterium and tritium in the plasma, helping to heat these ions to the point where they will undergo fusion reactions. Eventually, there will be sufficient heating in this manner to sustain the fusion reaction and ignition will be reached. There is speculation that the presence of large quantities of alpha particles may cause instabilities to appear in the plasma leading to excessive energy loss. Since no fusion plasma has reached ignition yet, investigation of such alpha particle instabilities has not been possible. Observations on TFTR where substantial fusion power has been produced, however, have indicated that such instabilities do not occur.



Major TPX components.

ommend the construction of a steady-state tokamak.[10]

In 1991, however, it became clear that BPX would not be built. The estimated cost of the facility had reached $1.4 billion and the Secretary of Energy Advisory Board (SEAB) Task Force on Energy Research Priorities recommended that DOE not proceed with BPX but concentrate on ITER.[11] Secretary of Energy Watkins ordered the cancellation of the project. Without the operation of a BPX, it became necessary to transfer its areas of investigation to ITER. In other words, ITER would have to be a test bed for examining the physics of burning plasmas in addition to its other missions. It appeared that the demise of BPX meant an extension in the physics operating phase of ITER.

In addition, the added responsibilities would increase the overall project risk. Since ITER's principal function was to be an engineering test fa-

[10] A number of proposals for steady-state tokamaks had been put forward by different researchers. See for example, General Atomics and Lawrence Livermore National Laboratory, Technology and Physics in the Tokamak Program: The Need for an Integrated, Steady-State R&D Tokamak Experiment," GA-A19305, UCID-21404, May 1988.

[11] Ronald C. Davidson, memorandum to John Sheffield, Oct. 30, 1991.

cility, it depended on most if not all of the physics being resolved prior to its operations. If there were substantial, unexpected problems with burning plasma stability—most likely as a result of the presence and actions of the alpha particles created by the D-T fusion reactions, a considerable delay in investigating the engineering issues of a fusion reactor would result. Nevertheless, the decision to cancel BPX plus the likelihood that no other ITER partner would build a burning plasma facility, made it necessary that ITER perform that role.

Also contained in the Task Force report was the suggestion that DOE look for a "less costly follow-on device" once TFTR concluded its experiments.[12] This charge was passed on to the Fusion Energy Advisory Committee. The committee accepted the Task Force recommendation to terminate the BPX program, and recommended a new experimental facility to follow TFTR. The recommendations of the two advisory groups focused on a device costing "in the $500 million class" that would "investigate improvements in the tokamak concept," support the ITER project, and maintain the scientific momentum of the U.S. program.[13] The SEAB report specifically requested that the new device investigate improvements "that could suggest new operating modes for ITER. . . ."[14] One of the major concerns of DOE at the time was that when TFTR finished its work in the mid1990s, there would be a decade at least in which there would be no major facility for U.S. fusion researchers to have access. ITER is not scheduled for completion until 2005 at the earliest.

Upon receiving the recommendations, DOE began to plan for the new machine. It set up a National Task Force on Post-TFTR Initiatives to develop a set of the most promising design options for more detailed study and to identify the preferred design options. The New Initiatives Task Force was asked to solicit a broad range of input from the fusion research community, including forming groups from the advocates of the various options. The Task Force was asked to provide DOE with guidance on the critical physics and technology issues that could be investigated by this new machine. While the Task Force was given considerable scientific and engineering latitude, the constraint that the construction cost of any new facility should be in the $500-million range was firm.

The Task Force finished its work in March 1992.[15] It recommended that the new facility be a long-pulse tokamak capable of investigating advanced operating regimes. It defined a long pulse as that required to ensure conditions within the plasma had reached a steady state, and that all equipment—power supplies, particle exhaust, etc.—would have to operate in a steady-state mode. In essence, this facility would fulfill the third of the four facilities recommended by FPAC, a steady-state advanced tokamak (SSAT). The Task Force recommended that the new facility limit most of its operations to deuterium plasmas, since providing the facility with the capability of extensive D-T operation at high energy gain would force the costs to go well beyond the $500-million limit. Finally, in a follow-on report in May 1992, the Task Force recommended superconducting magnets for the machine. All of this

[12] Ibid.

[13] Ibid.

[14] Charles H. Townes, letter to Secretary James D. Watkins, Oct. 20, 1992.

[15] J. Sheffield et al., "Report of the New Initiatives Task Force," Mar. 10, 1992.

could be accomplished, according to the Task Force, within the $500-million total project cost limit.[16] The recommendation was accepted by DOE and design has proceeded. The TPX proposal at an estimated construction cost of $597 million (in as spent dollars) was endorsed by the SEAB Task Force.

DESCRIPTION OF TPX

Scientific Features

The New Initiatives Task Force report identified the class of initiatives it reviewed as TPX. That name has now been adopted for the SSAT recommended by the Task Force. The mission of TPX is to "develop the scientific basis for an economical, more compact, and continuously operating tokamak fusion reactor."[17] Its principal feature will be its ability to operate at near steady-state conditions. TPX is being designed to achieve plasma pulse lengths of 1,000 seconds. This time is sufficient to ensure that the plasma has come to a steady-state equilibrium, both internally and with the surrounding vacuum vessel. To achieve this pulse length, a plasma current driven by the plasma itself—the "bootstrap" current—must be generated. In addition, current drive is to be assisted by the external heating mechanism. The bootstrap current, however, will make up about 70 to 90 percent of the total plasma current. While bootstrap current fractions in this range have been generated in some existing tokamaks, none of the experiments lasted long enough to reach a condition of steady-state equilibrium, which is one of the goals of TPX.

TPX will also attempt to operate in an advanced tokamak regime. This regime can be characterized by parameters that measure the potential power density of the fusion plasma if operated with deuterium and tritium, and the efficiency of the confinement system.[18] Higher values of the potential power density permit a tokamak operating with deuterium and tritium and generating a given amount of fusion power to be smaller and/or require a lower magnetic field, and, therefore, to be less costly. Higher confinement efficiency is also important because it allows the device to be smaller and/or operate with a lower magnetic field while confining the energy from the fusion reactions sufficiently long to produce significant energy gain.

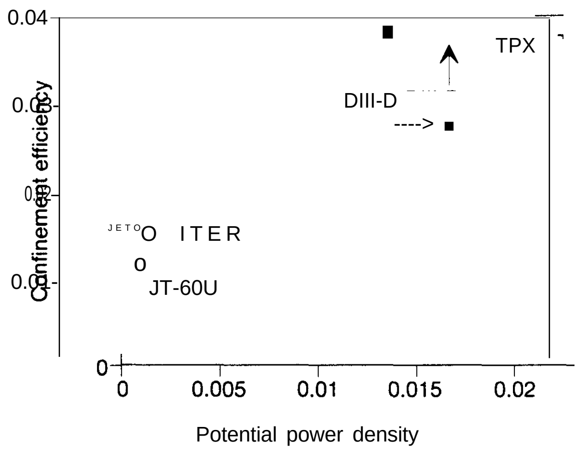
TPX is being designed to operate in a regime, defined by these two parameters, well beyond that of largest existing machines—JET and JT-60U (upgrade)—and greater than that assumed in the ITER design. Existing tokamaks with configurations closer to that proposed for TPX (most notably the DIII-D device at General Atomics) have achieved values of potential power density and confinement efficiency near that planned for TPX but not under steady-state conditions. Figure 3-1 shows the goals for TPX, their relationship to the other three machines and representative data points from the DIII-D device. The quantities on the two axes have no dimensions and are proportional to the parameter beta. As one moves up the

[16] The original charge to the Task Force (Davidson, op. cit., footnote 11) specified that the new device should be "in the $500 million" range. Although no indication was given in the memorandum about the reference point for those dollars, a September 1992 report by the Fusion Energy Advisory Committee on Program Strategy for U.S. Magnetic Fusion Energy Research stated that the amount was in "as-spent" dollars. The Task Force in its March 1992 report on the SSAT, estimated the cost of the machine at $429 million in fiscal year 1992 dollars. In its fiscal year 1995 budget submission to Congress, DOE gave a cost estimates of $597 million for total facility cost (actual construction cost) and $694 million for total project cost. These figures are in as spent dollars as calculated using DOE construction cost escalation rates. That is, this number is the sum of the dollar amounts in the years the money is actually spent. Taking the Task Force estimate and projecting it forward using the same rates yields a figure of about $540 million. Therefore, the original cost estimate was reasonably close—within 10 percent—to that determined after substantially more engineering design.

[17] The scientific features of TPX are described in detail in Princeton Plasma Physics Laboratory, "TPX: A National Facility for Steady-State Advanced Tokamak Research," briefing paper prepared for OTA, July 13, 1994; and see footnote 29.

[18] Both of the potential power density and confinement efficiency are characterized by a parameter called beta, which is the ratio of pressure exerted by the hot plasma to the pressure exerted by the external magnetic field.

FIGURE 3-1: Comparison of TPX Operating Regime to Other Tokamaks



SOURCE: Office of Technology Assessment, 1995

vertical scale at a given point on the horizontal axis, the magnetic field and/or machine size required to achieve a given fusion power gain decrease. Moving in the horizontal direction at a given point on the vertical scale allows a machine to produce a given amount of fusion power at a reduced magnetic field and/or size. In either case, the cost per unit of fusion power would decrease because of the importance of the magnetic field size to machine cost. The parameters selected for TPX are those that, if achieved, could considerably reduce the cost of an eventual tokamak fusion powerplant.

While the TPX design values have been reached on other experimental devices, they have not been matched at steady-state conditions. Indeed, in cases where similar values of beta-about 5 to 6 percent—have been reached, the plasma has proved unstable after a few seconds. A key goal of TPX is to investigate the physics necessary to eliminate this instability and allow the parameters to be held continuously as will be required in a tokamak fusion power reactor. Theoretical predictions show that these instabilities can be controlled by adjusting the shape of the main tokamak current. Such changes will be made on TPX with the external heating mechanisms (see below). Machines where the instability has been observed do not yet have as much flexibility for changing plasma current shape as is planned for TPX.

Reaching the parameters planned for TPX requires the ability to form the cross-section of the plasma into a shape resembling the letter D. This change has been shown to improve both confinement efficiency and potential power density. In short, such shaping allows a tokamak plasma to operate at a higher beta value than if it had a circular cross-section. Figure 3-2 shows cross-sections of various tokamak plasmas now in operation comparted to that proposed for TPX. Note the D-shapes for DIII-D and TPX compared to the circular cross section for TFTR. There are two parameters that characterize the plasma cross-section: elongation (referring to the stretching of the plasma) and triangularity (referring to the approximate triangular shape). A circular plasma cross-section has an elongation of 1 and a triangularity of 0. TPX is being designed to have an elongation of 2 and a triangularity of 0.8. These parameters are similar to those on the DIII-D device.

TPX will have three heating options. The plasma can be heated by injecting energetic beams of neutral particles-+ ailed neutral beam injection heating—as is now done on TFTR, or it can be heated by pumping electromagnetic power into the plasma. If the frequency of the electromagnetic power resonates with a characteristic frequency of the ions in the plasma, heating can take place. Two such frequencies are particularly useful. These methods are called ion cyclotron radiofrequency heating and lower hybrid current drive heating. External heating will also contribute to the steady-state current in the plasma and to shaping the plasma current for stability purposes as discussed above. As with the other characteristics discussed above, these heating methods have been applied to other tokamaks with success. Operating

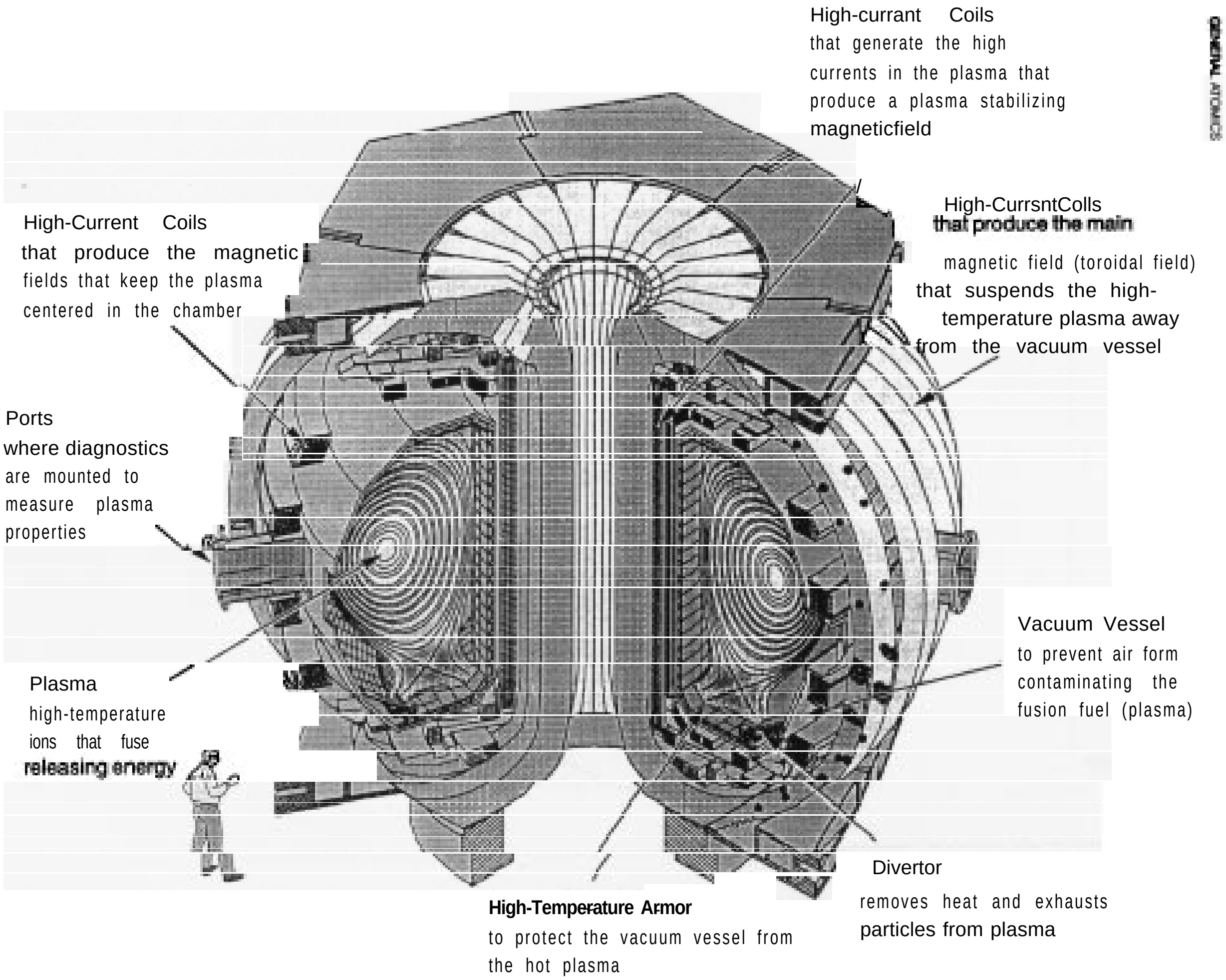


Diagram of General Atomics DIII-D Tokamak showing major components.

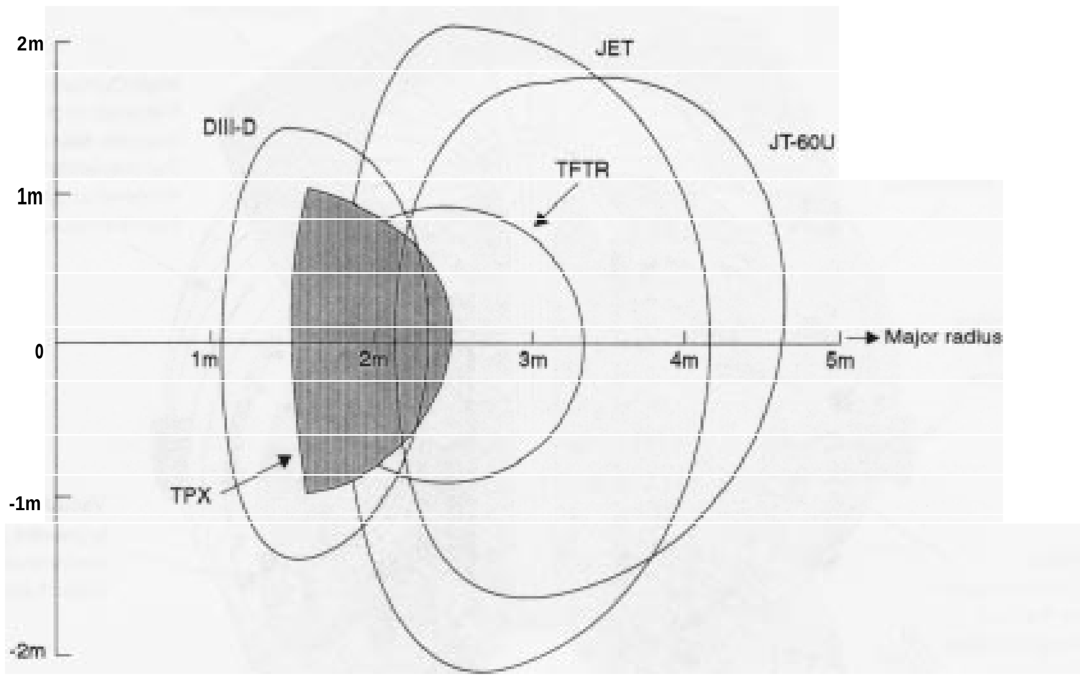
these heating methods in a steady-state environment, however, remains to be investigated.[19]

TPX will operate with deuterium to form the plasma since it is more desirable than hydrogen for achieving advanced operating conditions.[20] The use of deuterium, however, will produce fusion reactions and a significant quantity of neutrons (although considerably fewer than would result if deuterium and tritium were used). The presence of neutrons will require remote handling and shielding that would not be necessary if only hydrogen were being used. To achieve the performance sought for TPX with hydrogen, however, would require a much larger machine and neutral beam system than with deuterium alone. The net result of these two competing cost factors is a less costly machine with deuterium.

[19] It should be noted that current reactor design studies conclude that neutral beam heating and lower hybrid current drive are not likely to be practical for fusion powerplants.

[20] Robert Goldston, Princeton Plasma Physics Laboratory, personal communication, July 13, 1994.

FIGURE 3-2: Comparison of Plasma Cross-Sections of Selected Large Tokamaks



DIII-D = General Atomics, USA;
JET = Joint European Torus, European Community, Culham Laboratory, U. K.;
JT-60U = JT-60 Upgrade, Japanese Atomic Energy Research Institute, Japan;
TFTR = Tokamak Fusion Test Reactor, Princeton Plasma Physics Laboratory, USA;
TPX = Tokamak Plasma Experiment, Princeton Plasma Physics Laboratory, USA

SOURCE: Office of Technology Assessment, 1995, based on a figure provided by David Overskei, General Atomics.

Technological Features

There are several important technology issues that will be investigated on TPX.[21] First, TPX will be a fully superconducting tokamak. That is, all of the external magnet systems will be superconducting. While other tokamaks have had superconducting magnets, they have been confined to the main toroidal (donut-shaped) fields. The other major magnet system, called the poloidal field system, which is responsible for inducing the initial plasma current and shaping the plasma cross-section, has not been superconducting on any previous tokamak. The second feature will be the requirement that the superconducting magnets be capable of running essentially steady state. Because TPX will be operating with current pulses 1,000 seconds or longer, the toriodal magnetic field must be on continuously. Previous superconducting tokamaks have only had plasma pulse lengths of up to 60 seconds. It should be noted, however, that the superconducting toroidal field coils of the Tore Supra tokamak (a large tokamak

[21] For a discussion of the technological features, see Sheffield et al., op. cit., footnote 15.

operating in France) have been kept on for eight to 10 hours at a time.

Full-power operation of TPX is now projected to be about 200,000 seconds (55 hours) per year. While a small fraction of the total number of hours in a year, this period is considerably greater than current tokamaks. The limiting factor will be the degree of human access required for maintenance in the region outside the vacuum vessel. Because the vessel will become radioactive as a result of being struck by neutrons from the plasma, such access will require that the flux of neutrons be kept below a certain level, hence a limitation on the number of hours the machine can operate. This feature will be discussed more completely below. Not all of TPX experimental runs would be at the full 1,000-second pulse. Rather, runs with pulse lengths on the order of 100 to 200 seconds would be made testing various operating conditions. Only for those conditions that appear to be particularly interesting in terms of the TPX goals would 1,000-second or longer pulses be operated. Finally, the machine will be designed to operate for 500,000 seconds (about 140 hours) per year at reduced power. It is expected that these conditions will be used during startup of the machine.

Another critical area of investigation for TPX will be the divertor. Interaction between the plasma and the wall of the surrounding vacuum vessel takes place at the divertor. In any tokamak plasma, energy eventually escapes through the loss of the energetic particles making up the plasma and by radiation. The divertor is designed to capture and cool these escaping particles. The charged particles are also neutralized at the divertor and the resultant gas is exhausted from the vacuum chamber. Because the heat and particle load leaving a typical fusion reactor plasma will be very large, design of a divertor that can withstand such a load is critical. It is one of the factors that will determine the size of the tokamak. The higher the heat load that can be handled by a given divertor, the smaller the entire machine can be for a given power output. TPX is being designed to test different configurations. The TPX divertor system will be completely replaceable using remote handling technology. The divertor design is being made as flexible as possible. Finally, the steady-state nature of TPX is critical to investigating the steady-state behavior of various divertor arrangements.

Remote handling is another technological area that will be investigated on TPX. As described above, there will be significant numbers of neutrons formed during TPX operations. It will be necessary, therefore, to be able to make changes within the machine remotely using robotics. Since such handling will also be necessary on any fusion power reactor, the ability to test and develop these remote handling capabilities is a key feature of TPX. The radiation environment inside the machine will be kept low enough, however, to allow limited human access. The vacuum vessel, and many of its internal components, will be constructed of a material that produces a low quantity of radioactive byproducts when subjected to the flux of neutrons. Such materials are called low-activation materials. It is also possible that TPX can be a test facility for exposing different kinds of low-activation materials to a steady-state tokamak environment. Similarly, shielding in the wall of the vacuum vessel surrounding the plasma will be necessary to keep neutrons from the superconducting magnets. If neutrons reach the magnets in sufficient numbers, the resultant heating would cause them to heat up and lose their superconductivity. Testing shielding technologies will be useful for eventual fusion power reactors.

ISSUES

Relation to Existing Tokamaks

TPX is being designed as a national facility.[22] The design team is made up of members from various universities, other national laboratories, and representatives of industry. Once completed, TPX operations will be guided by an oversight council

[22] U.S. Department of Energy, op. cit., footnote 2.

with similar representation. Experiments will be performed by researchers from participating institutions throughout the nation under the guidance of this council. TPX will be integrated into the national information infrastructure so that researchers can perform experiments from their home institution. This situation is being created in order to facilitate one of the principal functions of TPX—that it be a centerpiece in maintaining a strong national research capability in fusion science and engineering.

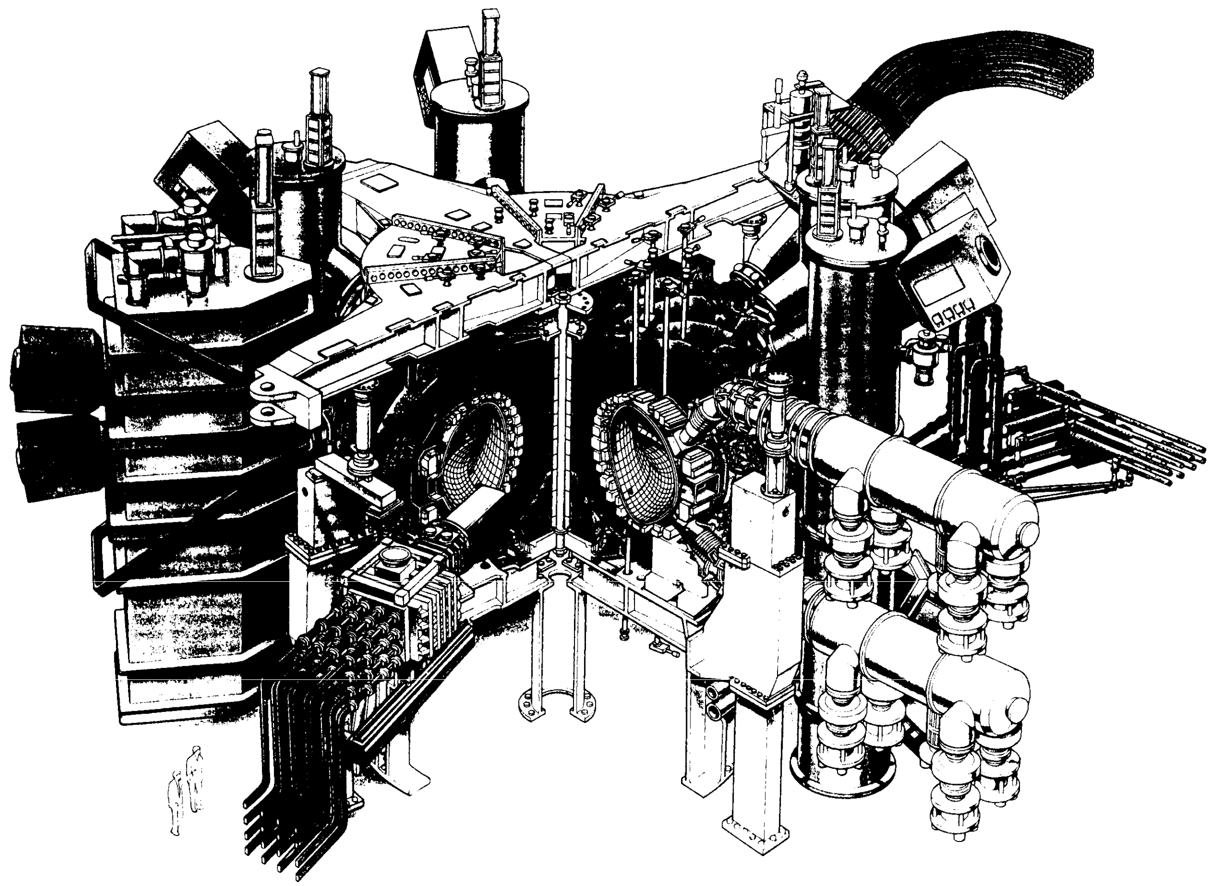
The New Initiatives Task Force made an assessment of several existing tokamaks to see if the goals of TPX could be met on one of them.[23] There are two other large, superconducting tokamaks in existence, the Tore Supra in France and the T-15 in Russia. Both devices have superconducting toroidal coils like TPX, but neither have superconducting poloidal coils. The Tore Supra appears to have the potential for long-pulse (about 600 second) operation. Both, however, have fusion plasmas with circular cross-sections and, therefore, are incapable of achieving the advanced operating parameters designed for TPX. The DIII-D device at General Atomics in San Diego has the necessary plasma shaping capability to test the advanced features and create the high bootstrap current fractions that are features of TPX. The DIII-D, however, cannot maintain the long pulses because its current magnet power supply configuration and plasma heating supplies are incapable of operation for the long periods needed for the 1,000-second pulses. Also, the DIII-D device cannot accommodate the large divertors planned for TPX without a significant reduction in plasma size.

The remaining large tokamaks are JET, JT-60U, and TFTR. None of these machines operates with superconducting magnets. Further, both JET and TFTR are committed for investigation of D-T plasma operation for the rest of their operational life. While capable of operating in advanced modes, as seen in figure 3-1, JT-60U will not be able to match the planned operating conditions of TPX, nor of sustaining very long pulses. Based on the capability of its magnet system, pulses of 45 seconds are about as long as could be expected on that machine. The Japanese have also carried out a conceptual design of a superconducting machine called the JT-60 Super Upgrade.[24] It would have many of the features planned for TPX and would be larger and more powerful. Construction has not been approved, however, and its fate may depend on funding resources in Japan and whether TPX is built. In any case, the JT-60 Super Upgrade is seen as possible by Japanese research funding authorities only if ITER is not sited in Japan.

Finally, none of the current machines can match the planned, high-duty cycle of TPX. A key parameter in determining duty cycle is the annual flux of neutrons produced by fusion reactions of the deuterium used for TPX plasma. These neutrons will impinge on the inner wall of the vacuum vessel and on the divertor resulting in a steady buildup of radioactive material in these structures. In addition, neutrons that escape the ports in the vacuum vessel will activate structures outside the vessel. To keep the activation levels of such material below that which can be handled without costly procedures puts a upper limit on the neutron flux that can strike these structures. Also, DOE's site boundary dose limits (30 times lower than background) must be observed. TPX is being designed to accept an annual neutron flux of $6x10^{21}$ neutrons. The other machines are limited to neu-

[23] Sheffield et al., op. cit., footnote 15, ch. 3.

[24] H. Ninomiya et al., "Conceptual Design of JT-60 Super Upgrade," paper presented at the 15th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville, Spain, Sept. 26 - Oct. 1, 1994.



The JT-60U tokamak in Japan.

tron fluxes 10 to 100 times less than TPX design because of their structural materials. Table 3-1 summarizes the principal parameters of the tokamaks discussed in this section compared to TPX.[25]

Relation to ITER

The FPAC report included both an engineering test reactor and a steady-state advanced tokamak among its recommended facilities. Much of the conceptual design activity (CDA) work on ITER was complete before the TPX initiative began, however, and the final report of the CDA was vague about whether a TPX-like machine would be operative in time to provide ITER with any design or operational guidance.[26] Indeed, it was assumed at the time that a burning plasma facility would be the one constructed. The ITER CDA report did define physics and technology R&D that would be needed to "validate the scientific and technical basis and assumptions" for the ITER design.[27] Included were several of the areas that are planned to be investigated by TPX such as long-pulse operation, improved divertor performance,

[25] Sheffield et al., op. cit., footnote 15, ch. 3; and Princeton Plasma Physics Laboratory, op. cit., footnote 17.

[26] International Atomic Energy Agency, *ITER Conceptual Design Activities: Final Report,* ITER Documentation Series, No. 16 (Vienna, Austria: 1991).

[27] Ibid., p. 14.

TABLE 3-1: Tokamak Comparison Table

Parameter	TPX	TORE SUPRA	T-15	DIII-D	JT-60U	JET
Major radius (meters)	2.25	2.38	2.43	1.67	3.4	3.1
Minor radius (meters)	0.5	0.75	0.70	0.67	0.85	1.1
Toriodal field (T)	4	4.5	3.5	2.1	4.2	3.4
Plasma current (MA)	2	2	1.4	2.1	6.0	6.0
Elongation	2	1.0	1.0	2.0	1.6	1.8
Pulse length (see)	1,000	**20**	?	**10-60**	**20-30**	**15-30**
Neutron budget (ns/yr)	6x102 l	$1.2X10^{20}$	?	$3X10^{18}$	$<10^{21}$	$>10^{21}$
Country	Proposed U.S.	France	Russia	Us.	Japan	U.K.

KEY
JET = Joint European Torus
MA = mega-amperes
ns/yr = neutrons per year
T = tesla
TPX = Tokamak Physics Experiment

SOURCE: J. Sheffield et al., "Report of the New Initiates Task Force," Mar. 10, 1992.

superconducting magnets, remote handling, and plasma heating and current drive systems. The ITER CDA assumed that this research and development (R&D) would be done on existing tokamaks and that ITER would be responsible for integrating all these features along with its other goals.[28] On that basis, one could conclude that the ITER project was proceeding under the assumption that no steady-state advanced tokamak would be built.

While it is planned that TPX will investigate many of these ITER CDA R&D needs, operation is not scheduled to begin until ITER construction is underway according to the current plans. This situation was recognized by the team that developed the report on TPX (SSAT) to the New Initiatives Task Force early in 1992. The report stated that TPX operations would be able to provide valuable operating experience on long-pulse, high-duty factor operation for later operations of ITER.[29] In addition, construction of the superconducting magnets would give U.S. industry important experience as a prelude to the task of constructing the ITER magnets. Finally, TPX would serve as a central research facility for U.S. researchers while ITER was under construction.

The ITER design activity seems to be attempting to make a greater connection between it and TPX. There have been discussions between TPX and ITER design teams about divertor systems. Currently, the two machines are using different divertor designs with ITER proposing a more conservative configuration. TPX, however, has the capability of investigating the divertor configurations planned for ITER. Comparison of the different designs should permit TPX to make important contributions to the divertor choice for DEMO. A more important connection concerns the advanced operating mode investigations of TPX.

[28] Ibid.

[29] Keith Thomassen et al., Lawrence Livermore National Laboratory, *Steady State Advanced Tokamak (SSAT); The Mission and the Machine* (Springfield, VA: National Technical Information Service, March 1992).

Currently, ITER is being designed fairly conservatively in terms of the confinement efficiency and potential power density parameters. From figure 3-1 above, it lies considerably below the design variables for TPX. Originally, ITER was to be configured to operate in a regime closer to that of TPX. These parameters were changed because such operation would have entailed more risk for ITER, since the fusion power produced would have taxed the limits of the materials used for the vacuum vessel. While TPX proposal did not spark these changes, results from TPX related to the advanced operating regimes, as discussed below, would be useful for ITER.

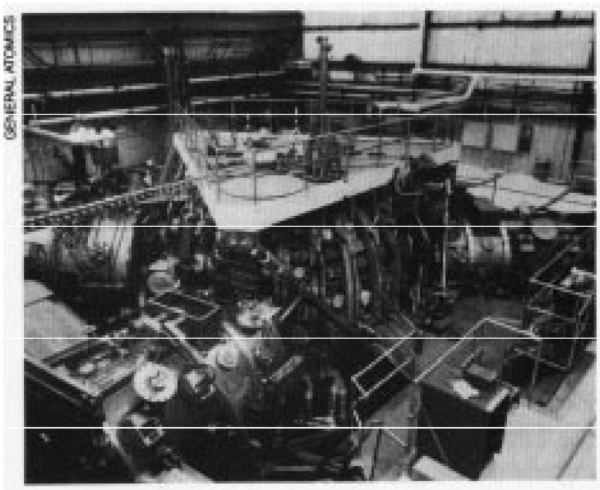
The ITER design group recently indicated its desire to maintain the flexibility of performance in steady-state advanced tokamak regimes in the later phases of its operation to permit study of advanced operating regimes in ITER. Significant upgrades to auxiliary systems may be required for these tests, but it appears that ITER could ultimately approach TPX conditions in a D-T plasma operating at high energy gain. A major question is the cost involved. To build in the flexibility so that ITER could fully explore this advanced, steady-state regime may be very expensive. Recent work has shown that while ITER is being designed for lower elongation and triangularity (see figure 3-1) than TPX, calculations indicate that values approaching those of TPX can be attained in ITER at reduced plasma current.[30] At this time, the ITER design team seems intent on preserving this capability. The ITER interim design, expected in June 1995, should allow a better assessment of whether this is indeed the case.

Achieving the ideal operating conditions will require optimizing several parameters. Whether TPX, with its ability to shape the plasma cross-section to a greater degree than ITER, is more successful than ITER at reaching these conditions remains to be determined by experiment. Results from TPX in this context should be valuable for ITER.

In addition, in many of the technology areas—such as superconducting magnets and remote handling and shielding—ITER will have to be operating at least on par with TPX if not in advance of it, since ITER demands will be substantially greater due to its D-T operation. Experimental results on TPX, if they precede ITER operation by a sufficient period, could be of value.

Unless they can be tested in ITER, there will likely be considerable uncertainty about integrating TPX results with those from ITER in designing and building 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. As discussed above, these areas can be incorporated in ITER from the start or be integrated into it after testing elsewhere, preferably on TPX. 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. Indeed, if operation in the advanced regimes has not been demonstrated, the economics of a tokamak fusion powerplant may be not be attractive enough to be accepted by the market. Demonstrating advanced operations may be the most important contribution of TPX. TPX, therefore, is designed to be upgradeable for operation with deuterium and tritium. Doing so, however, would eventually add to the cost of TPX. Such expenditures may prove beneficial since D-T operation in TPX could complement D-T experiments in ITER and provide important data for

[30] W. Nevins et al., "ITER Steady-State Operation and Advanced Scenarios," IAEA-CN-60/E-P-5, paper presented at the 15th International Conference on Plasma Physics and Controlled Nuclear Fusion, Seville, Spain, Sept. 26-Oct. 1, 1994.



The DIII-D Tokamak at General Atomics in San Diego.

DEMO. It is likely that DEMO will be designed rather conservatively because of the potentially high cost of that machine. To the degree that advanced operation has not been tested in a D-T, steady-state device such as ITER, the risk of incorporating that feature into DEMO may be too great.

▮ Stand-Alone Machine

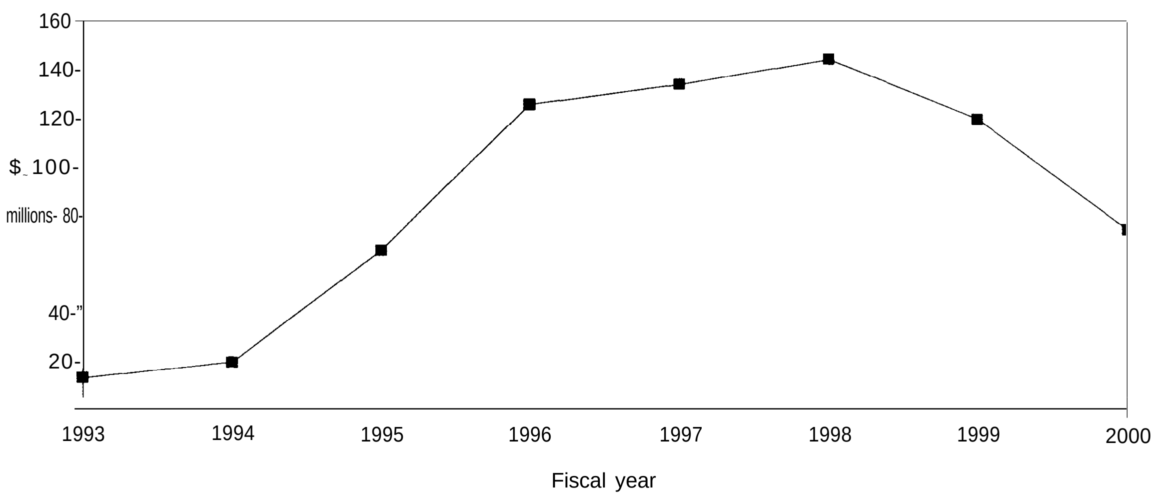
Supporters of TPX argue that the machine's value is not dependent on the ITER even though many of the scientific and technical issues that TPX will investigate are important for ITER. They say that some of the results from TPX will be useful regardless of the path fusion power development takes. In particular, operation of superconducting magnets and remote handling will be necessary on arty magnetic fusion reactor. In addition, there will be need for a divertor or similar device to remove heat and particles from a burning plasma. There-sults of physics investigations on steady-state and advanced operations can also be useful to a variety of other magnetically confined concepts since they, too, will have to operate continuously and will be concerned with some of the same issues about power density and confinement efficiency gain. Much of the steady-state and advanced operation issues to be investigated by TPX, however, are unique to the tokamak concept. For that reason, the results of the advanced operation experiments may be essential in evaluating the tokamak against alternative concepts should the latter fusion program be redirected toward more effort on such concepts.

Another important function of TPX, as described above, is to serve as a national facility. Without such a machine, there does not seem any prospect for a new large, magnetic fusion experimental facility in the United States in the next several years after TFTR shuts down. Several other U.S. tokamaks would remain in operation, however, the largest of which is the DIII-D facility at General Atomics in San Diego. While possessing many of the features of TPX, DIII-D is not now capable of steady-state operation for the reasons described above. In addition, it is not now a national facility in the sense that TPX is intended to be. Access to DIII-D by researchers outside of General Atomics, however, has been quite good.

Another possible scenario for the magnetic fusion energy program is that ITER is indefinitely postponed, but no other alternative concept emerges to challenge the tokamak.[31] In that case, TPX could be of even more value than currently is the case. As previously stated, the physics and technology it is investigating are fundamental for the development of any tokamak-based fusion power reactor. It also seems clear that while TPX will expand the state of knowledge about advanced tokamak operation, successful steady-state operation in that regime is by no means certain. Particular issues that need resolution concern how steady-state operation affects density and current profile-shaping for generating the bootstrap current and attaining higher values of potential power density and confinement efficiency. Similarly, there is still much R&D to be done to come up with a divertor that can operate reliably

[31] For one discussion of different timing and mix of major tokamak facilities leading to a demonstration powerplant, see Stephen O. Dean, Fusion Power Development Pathways," *Journal of Fusion Energy,* vol. 12, No. 4, 1993, pp. 415-420.

FIGURE 3-3: Estimated TPX Construction Funding Schedule



SOURCE Off Ice of Technology Assessment, 1995

under steady-state conditions. If TPX is built and these important physics and engineering problems are solved, the possibility of developing a successful tokamak-based fusion power reactor would be significantly higher.

■ cost

As proposed in the DOE fiscal year 1995 budget request to Congress, the total project cost estimate of TPX is $694 million to completion. This estimate includes $597 million for actual construction and $97 million for associated research during the construction period and other related costs. These costs are all in as spent dollars. The cost profile as envisioned in the fiscal year 1995 request is given in figure 3-3. This plan called for $66.9 million in fiscal year 1995. Congress, however, appropriated $42 million and did not grant approval to start construction. At this time, the fiscal year 1996 budget request is uncertain. In addition, the spending profile will also change, but, assuming project construction is approved, the annual amounts needed are not likely to decline from those shown. Currently, DOE is projecting annual operating costs of $150 million (in fiscal year 2000 dollars) for the 10-year life of the facility.

The budget requirements for TPX construction when combined with DOE commitments to the ITER program, even before its construction, would result in a large increase in the total MFE budget unless the base program is greatly reduced. While some reduction can be expected as TFTR operations are phased out, it is not likely to be sufficient to keep the total budget requirements from growing sharply. At the same time, there have been calls to reduce the magnetic fusion energy budget by as much as 50 percent. It is clear, therefore, that gaining approval to begin TPX construction is likely to be difficult. Given the Japanese interest in a machine with similar characteristics—the JT-60 Super Upgrade—it may be desirable to explore the possibility of making TPX an international venture just as the ITER project, or otherwise integrating it more fully into the international fusion energy effort.