White Paper on
Magnetic Fusion Program Strategies

Prepared for

The President's Committee of Advisors on Science and Technology

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1. Introduction

Dramatic progress has been made in magnetic fusion research during the past decade, culminating in the recent production of over 10 MW of fusion power in the Tokamak Fusion Test Reactor at Princeton University. These results are the fruits of a sustained worldwide research effort on tokamaks since the early 1970s. During the same period, international collaboration, long a hallmark of the fusion program, has expanded beyond the close coordination of programs and facilities to the beginnings of joint international implementation of major projects. Fusion has the technical foundation to proceed, and the international basis for substantial cost-sharing.

The remaining technical issues to be addressed in developing practical fusion power fall into five generic themes. The remaining plasma physics issues deal with: (i) the behavior of burning, or self-ignited, plasmas, and (ii) the development of tokamak operating modes, or of alternatives to the tokamak, that best meet the requirements of a power system that is attractive by the criteria of safety, economics and public acceptance. The non-plasma-physics issues deal with: (iii) developing the non-nuclear technologies required for fusion, such as large-scale superconducting magnets and high heat-flux components; (iv) developing the tritium-breeding blanket and other nuclear technologies, and (v) developing and testing the low-activation materials necessary to realize fusion's full potential as an environmentally benign power source.

Progress in fusion research depends on a continual renewal of facilities to qualify newly-developed technologies and to extend scientific understanding. However, no construction of major new magnetic fusion research facilities has been initiated in the U.S. since the late 1970s. Advanced conceptual design is complete for the next step experimental device in the U.S. program, the Tokamak Physics Experiment (TPX), and the TPX Project now awaits construction approval by the U.S. Congress. The major focus of the international fusion program, the International Thermonuclear Experimental Reactor (ITER), is now halfway through its Engineering Design Activity, which is scheduled to be completed in 1998. This joint effort in which all partners share in the costs and benefits, must be supported by strong domestic programs.

At this time of great technical success, and need for new facilities, the future of magnetic fusion research is uncertain. There are predictions of future energy shortages and of severe environmental impacts from increased fossil fuel consumption by a rapidly increasing world population. However, there is presently no perceived urgency among policymakers or the public for the development of new, environmentally attractive energy sources. Indeed energy R&D appears to be a favored target for budget reduction. It is against this difficult policy background that we members of the U.S. magnetic fusion research community present our vision for the future of fusion energy research.

In this white paper, following a summary in Sec. 3 of DOE's current fusion development plan, in Sec. 4 we present an alternative program strategy designed to achieve the major objectives of the current strategy without requiring increases in the U.S. fusion budget over the present level.

2. The argument for fusion

The argument for fusion energy is clear. Fusion is potentially a limitless energy source with much less environmental impact than fossil or nuclear fission sources. Fossil sources are limited and will contribute to significantly increasing amounts of carbon dioxide in the atmosphere if they serve as the major energy source for a growing world population. Fusion is inherently safer than nuclear fission energy, primarily because only minutes' worth of fuel are contained within a fusion reactor at any moment, compared with years' worth of fuel in a fission reactor. Also, since a fusion reactor produces no long-lived fission products and actinides (e.g., plutonium), the danger and lifetime of radioactive waste products can be many orders-of-magnitude lower.

The environmental impact of fusion is also likely to be much less than that of large-scale renewable energy sources. Large tracts of land are not required for energy generation, as with wind, biomass, and solar energy, and massive energy storage and transmission systems are not required, since a fusion plant's operation is largely independent of weather and geography. Thus if fusion energy can be made a commercial reality, it presents a very attractive prospect.

The cost to the United States of developing fusion energy has been estimated at $20-30B, resulting in a first commercial power plant around the year 2040. This substantial cost should be put in the perspective that at present spending rates the U.S. economy will expend $22T on the purchase of energy between now and 2040, so the "tax" for the development of fusion corresponds to 0.1-0.15% of these expenditures.

3. DOE's current fusion development plan

The current plan for the development of fusion energy put forward by the Department of Energy calls for roughly a doubling of the magnetic fusion budget in the period 1997 - 2006, compared with the rate of spending in 1996. The elements of this plan include:

- International Thermonuclear Experimental Reactor (ITER)
- International Materials Test Facility (MTF)
- U.S. Tokamak Physics Experiment (TPX)
- U.S. Base Program in Science and Technology

The mission of the ITER device is severalfold. First, it is to achieve a self-sustained long-pulse "ignited" burn in a deuterium-tritium plasma. This is the condition where the fusion power produced in the form of charged particles sustains the temperature of the burning plasma. Next, ITER is to provide integrated testing of the non-nuclear technologies required for fusion: large superconducting magnets, remote maintenance, high-heat-flux components, and high-power, long-pulse plasma heating systems. Finally, in its later stages, ITER is to provide a test-bed for the "blanket" components which surround the plasma, and are used to breed fresh tritium from lithium.

The mission of the MTF is to develop long-life, low-activation materials for fusion applications. A point neutron source, based on high-current accelerator technology, will provide a user facility for high-fluence testing of materials in a simulated fusion neutron environment.

The mission of the TPX is to develop the scientific basis for compact, cost-competitive, steady-state tokamak fusion power plants. The present understanding of tokamak physics is adequate to support the step to ITER, but an attractive power plant will need to be more compact than ITER, and must operate continuously. TPX is designed to extend recent high-performance tokamak results to steady-state conditions, so that advanced steady-state tokamak operating modes can be developed for a more attractive tokamak fusion power plant. At the same time TPX incorporates many of the technologies of a fusion power plant (superconducting magnets, high-heat-flux components, internal remote maintenance, etc.) and so will provide U.S. industry with valuable experience in key fusion technologies.

The base program in science and technology supports these major projects with theory, smaller-scale experiments, including alternatives to the tokamak, and technology development. Much of the theoretical and experimental basis for the ITER and TPX tokamak designs has come out of the base program. The technologies required for these devices have also been developed in the base program. ITER will create a special need for the base program to develop blanket modules to be tested in its neutron environment.

The cost to the U.S. of these program elements, over the ten-year span of 1997 - 2006, can be estimated in as-spent dollars:

- International Thermonuclear Experimental Reactor (ITER) — $3.25B
  - Total cost presently estimated by DOE is $13B.
  - If the U.S. is not the host country, the U.S. share is estimated to be 25%.
- International Materials Test Facility (MTF) — $0.375B
  - Total cost presently estimated at $1.5B.
  - If the U.S. is not the host country, the U.S. share is estimated to be 25%.
- Tokamak Physics Experiment (TPX) — $1.49B
  - Construction cost for first plasma in 2001: $0.74B.
  - Full operation for 5 years: $0.75B.
- Base Program in Science and Technology — $2.4B
  - Also includes blanket module development for ITER.
  - Also includes materials development for testing in MTF.
  - Also includes research on alternatives to the tokamak.

Total cost to U.S., 1997 - 2006 — $7.5B

This corresponds to an average spending rate of $750M/year during this ten-year period, which would represent about a factor of two increase over present spending levels. Time profiles for TPX and ITER spending can be found in the table at the end of this document.

We members of the U.S. magnetic fusion research community believe that these program elements address the issues critical to the timely development of fusion energy as an attractive new energy source.

4. Alternative international fusion program

The program plan outlined in the previous section is attractive from the perspective of the development of fusion energy in as timely a manner as possible. However we recognize that budget stringencies form a real constraint, and alternative plans must also be examined. If financial constraints dictate that budget levels for magnetic fusion research will not increase dramatically in the next few years, then it is necessary, unfortunately, to find alternative means to achieve both the physics and technology goals of the ITER Project. However, it is clear that the international coordination provided by the ITER Process must not be lost, since international resources must still be leveraged to achieve these goals. An important element in preserving the ITER Process is to maintain the U.S. commitment to the

Engineering Design Activity, albeit perhaps at a reduced level, as the international emphasis shifts to other areas.

In the absence of the ITER device it would still be necessary to address the ITER mission elements of long-pulse ignition, tokamak technology development, and blanket component testing. The TPX mission of tokamak concept improvement would still be needed, as would the MTF mission of materials development. The following is an example that shows how a different mix of international program elements would meet these needs, although at a slower pace and with less integration than in DOE's current development plan. The ITER Process would shift to international program coordination and to construction of the MTF Project on a fully international basis.

- Long-pulse ignition experiment
  - This device would address the issues of self-sustained plasma burn.
  - It would also address some of the technology issues of ITER, especially in the areas of high-heat-flux components and remote maintenance. Most likely it would use copper-coil magnet technology, perhaps with active liquid nitrogen cooling, as proposed in the European HLT (High-Performance Long-Pulse Tokamak) pre-conceptual design.
- Large-scale tokamak technology development
  - Absent ITER, it will still be necessary to develop large-scale superconducting coils and other steady-state technologies. The present Japanese JT-60SU pre-conceptual design addresses these issues.
- Tokamak concept improvement
  - TPX addresses the mission of advancing the scientific basis for an advanced high-performance tokamak, as in the current DOE fusion plan.
  - TPX also provides the U.S. with direct experience in many aspects of tokamak technology, such as superconducting magnets, internal remote maintenance, and high-heat-flux components.
- International Materials Test Facility
  - This facility plays the same role as in the current DOE fusion plan.
- Volume Neutron Source (VNS)
  - Blanket component testing might be done in a much smaller facility than ITER, specifically designed for this purpose.
  - The physics and technology for VNS would be developed during the period 1997 - 2006, for example in TPX, but construction would begin beyond this time horizon.

International coordination and planning, and sharing of techniques and results should be fostered through a continuation of the ITER Process. (It is also possible that Europe and Japan would choose to construct the ITER device itself without U.S. participation. This alternative seems less likely than the above scenario, since the cost to the host country would be in the range of $8.7B, while the cost to the non-host would be approximately $4.3B.)

The cost to the U.S. of the program outlined here, over the ten-year period 1997 - 2006, can be estimated in as-spent dollars as:

- Long-pulse ignition experiment
  -- Likely cost ~ $3B, likely location: Europe.
- Tokamak technology development
  -- Likely cost ~ $3B, likely location: Japan.
- Tokamak Physics Experiment (TPX) $1.1B
  -- Construction cost for first plasma in 2003: $0.85B.
  -- Slower start on operation for 3 years: $0.25B.
- International Materials Test Facility (MTF) $0.375B
  -- Total cost presently estimated at $1.5B.
  -- If the U.S. is not the host country, our estimated share would be 25%.
- Base Program in Science and Technology $2.1B
  -- Also includes materials development for testing in MTF.
  -- Also includes research on alternatives to the tokamak.

Total cost to U.S., 1997 - 2006 **$3.6B**

This budget estimate assumes that each of the first three program elements would be constructed fully at the expense of its home party. In particular TPX would be funded and structured as a U.S. national construction project, as now planned. However, operations and upgrades of each of the three national projects would include strong international participation. The Materials Test Facility would be constructed fully internationally, and operated as an international user facility. (Cost profiles for a stretched TPX schedule can be found in the table at the end of this document.)

This program requires an average spending rate of $360M/year during this ten-year period, about comparable to present funding levels. Completion of TPX is delayed by two years in order to level out spending curves, but an increase above present funding levels could be used to move this completion date forward and to accelerate operations.

At significantly lower budget levels than $360M/year, and without TPX, the U.S. fusion research program strategy would exploit current facilities, addressing insofar as possible the five areas of fusion development identified in the Introduction. However, such a program would be severely limited in what it could offer the international fusion development effort, after these facilities have completed their productive operation, because it would have failed to provide the new facilities that are required to make substantial progress in the first decade of the next century. Under these circumstances, the U.S. would after a few years cease to be a strong participant in the world effort to develop fusion power.

5. Conclusions

We believe that fusion energy has the potential to be a critical technology for the next century. It offers the promise of a limitless energy source with modest environmental impact compared to fossil, fission or renewables. Despite dramatic recent progress, the development of fusion still requires a strong commitment from the federal government, since it cannot be done by private enterprise. We strongly support the DOE's plan for fusion development, which requires a factor-of-two increase in funding levels. We recognize, however, that fiscal constraints may make this impossible, so we have outlined an alternative program which would carry fusion research forward at a slower pace, but with continued significant international collaboration in a way that allows the United States to participate in the development of this critical technology.

TPX and ITER Construction and Operation Funding Profiles

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total	Source
TPX	139.4	136	134.9	134	150	150	153	156	160	164	1477	DOE
first plasma 2001												
TPX-Stretch	83	97	98	109	109	109	109	120	130	140	1104	PPPL
first plasma 2003												
ITER EDA	84.5	87.1	0								171.6	DOE
ITER Siting	10	8	4								22	DOE
ITER Increment	10	10	0								20	DOE
ITER Construction (1/4 of $13B)			245	300	460	507	457	470	345	357	3141	DOE
ITER	104.5	105.1	249	300	460	507	457	470	345	357	3355	DOE
first plasma 2007												

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