What Would Be Lost, and Recommendation

The three U.S. experimental programs have a superb track record of collaborative discovery and innovation within the U.S. and within the international program. They have the most extensive set of diagnostics, heating and fueling systems, and control systems, as well as a strong connection to theory and superb modeling capability. Alcator C-Mod is the world's only diverted, high field tokamak, featuring all radio frequency heating and high power flux to a unique metal wall/ divertor. DIII-D is the best equipped and most flexible tokamak in the world. NSTX has the most capabilities of any spherical torus facility, and it can study electromagnetic effects at ultra-high β values. In total, they have a unique set of capabilities for a coordinated effort to explore advanced plasma science relevant to fusion in the range of all key parameters – except machine size and alpha heating power. Moreover, each program plays a major role in the education of the next generation of fusion energy scientists and engineers.

What Would Be Lost from Scientific Goals and Expected Accomplishments

<u>**Macroscopic Plasma Physics**</u> *(cf. this report Sec. 2.1):*

Substantial progress will be achieved in understanding the role of magnetic field structure on plasma confinement, both for fundamental science and in direct preparation for ITER [**All**]. Experiments to understand pressure limits in rotating plasmas with resistive walls should be completed, and studies of active stabilization without rotation will be underway [**DIII-D, NSTX**]. The understanding of neoclassical tearing instabilities and edge localized modes will be complete and documented, including methods of control and suppression [**All**]. An understanding will be developed of mode stabilization due to plasma rotation, as well as the physical processes responsible for increased drag due to plasma modes **[DIII-D, NSTX]**. Studies will be performed of different types of plasma self-organization and their interaction with external control methods [**All**]. Methods will be developed to sustain the plasma duration, including Òhybrid operating modesÓ for ITER **[All].** Scientific issues associated with the integration of high plasma pressure, good confinement, and efficient sustainment of plasmas, including bootstrap current, will be investigated [**All**]. The mechanisms for relaxation and reconnection of the magnetic field will be identified [**DIII-D, NSTX**].

What Would Be Lost from Scientific Goals and Expected Accomplishments

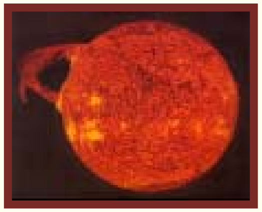
Multi-scale Transport Physics *(cf. this report Sec. 2.2):*

The goal of developing a predictive capability for ion thermal transport is within reach [**All**]. Turbulence-driven electron cross-field thermal transport remains to be understood at the fundamental level. As with ion transport, studies over a parameter range broader than that accessible by one machine will be required. The three US facilities are sufficiently distinct to provide this range, and are experienced in carrying out the necessary comparisons. Small-scale turbulence diagnostics are being implemented to explore the role of turbulence on electron thermal transport, and within ten years the full wavelength and frequency ranges of the dominant turbulence should be identified. Loss of any of the three facilities will severely compromise this research area [**All**]. Particle and momentum (rotation) transport studies are less mature, and there are known surprises that must be understood; within five years, some convergence can be expected on which physical mechanisms are most important [**All**]. A more complete understanding of the conditions and thresholds for the formation of edge and core transport barriers, and their dynamics, will be obtained. The expectation is that transport barriers can then be used as a tool to control the levels of core transport [**All**]. Within ten years it will be possible to compare theoretical and numerical models with experimental data on zonal flows and their effects [**All**]. Large scale flows in plasmas without dominant external flow drive will be documented and analysis should enable predictions for ITER [**All**].

What Would Be Lost from Scientific Goals and Expected Accomplishments

<u>Plasma-Boundary Interfaces</u> *(cf. this report Sec. 2.3):*

First-principles models of the edge pedestal will be available to reproduce many of the measured characteristics of the plasma boundary in one or more fusion experiments [**All**]. Experiments will be carried out to validate these plasma-boundary models for ITER [**C-Mod, DIII-D**]. The physics of edge localized modes and their impact on the scrape-off layer will be largely understood, enabling the development of new mitigation techniques and operational regimes to minimize their impact [**All**]. The fundamental characteristics of scrape-off layer turbulence in high-confinement plasmas will be determined [**All**]. There should be sufficient data to quantify the major impurity sources, including divertor and first wall erosion and deposition rates [**All**]. The distribution of tritium that is expected to be trapped in carbon-based plasma-facing components will be largely understood in terms of plasma conditions observed in present experiments. Candidate techniques for tritium removal will be developed in carbon-based components [**DIII-D, NSTX**]. Operation with potentially low tritium retention will be performed with a purely metallic wall [**C-Mod**]. Alternative high-heat flux components such as liquid lithium divertors will be qualified [**NSTX**]; tungsten brush divertor components and all-metal walls will be utilized [**C-Mod**].



What Would Be Lost from Scientific Goals and Expected Accomplishments

<u>Waves and Energetic Particles</u> *(cf. this report Sec. 2.4):*

Externally launched waves are the only means of providing core plasma heating and the necessary precision control of the current profile in advanced tokamak scenarios in ITER and in future experiments. Considerable advances are expected in developing the fundamental physics models for wave coupling, propagation, absorption, and plasma responses that will enable coupling on critical time scales with plasma stability and transport models. Experiments with lower hybrid and ion cyclotron waves [**C-Mod**], electron and ion cyclotron waves [**DIII-D**], fast waves and electron Bernstein waves [**NSTX**] will validate these models. Improved understanding of radio frequency sheath effects and antenna loading will be achieved [**All**], and with an ITER-like scrape-off layer [**C-Mod**]. Wave heating and current drive simulations will be benchmarked in support of ITER [**C-Mod, DIII-D**]. Prior to the advent of full burning plasma operation in ITER, progress is expected in understanding the behavior of energetic particles (generated by auxiliary heating) and of the unstable waves that can be excited by them with the use of existing facilities, and in improving theory and simulations for energetic particle dynamics [**All**].

What Would Be Lost from Scientific Goals and Expected Accomplishments

<u>**Fusion Engineering Science**</u> *(cf. this report Sec. 2.5):*

Considerable progress is expected in developing the knowledge base required to determine performance limits and identify innovative solutions for the plasma-facing components and divertor materials [**All**]. Advances will be made in fueling, wave heating, current drive, and plasma control systems [**All**]. Support will be provided for the construction and reliable operation of ITER, including disruption mitigation [**C-Mod, DIII-D**] and support for a candidate Component Test Facility [**NSTX**].

What Would Be Lost from Scientific Goals and Expected Accomplishments

<u>Burning Plasmas</u> *(cf. this report Sec. 3):*

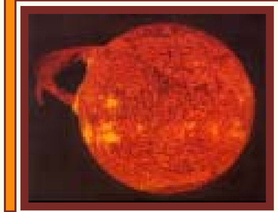
The three U.S. machines taken together provide a wide set of parameters to determine relevant physics parameters for ITER and future burning plasma devices [**All**]. The physics of the edge pedestal is critical for ITER, and the three machines all contribute to this ongoing effort [**All**]. Control of exhaust heat and particles is being approached with different wall materials in the three machines [**All**]. Experiments on the understanding and control of ELMs, a short burst of heat flux, will be undertaken on all three machines, along with coordinated scaling experiments on international machines [**All**]. The physics of plasma rotation and its role in MHD stability will be investigated; this is important in determining whether ITER will be stable to various modes such as the resistive wall mode [**DIII-D, NSTX**]. Experiments on facilities with no apparent torque input when only radio frequency waves are used for heating and current drive [**C-MOD**] will be compared with experiments in facilities in which the torque can be varied [**DIII-D, NSTX**].

What Research Opportunities Would Be Lost

<u>C-Mod</u> is distinguished by the following salient characteristics: (1) it operates at higher magnetic fields than any other existing divertor tokamak, and over a range that spans the ITER magnetic field value; (2) it has all-metallic (high atomic number) tungsten and molybdenum wall armor and divertor plates; and (3) its non-inductive heating and current drive are supplied entirely by flexible radio frequency techniques. C-Mod is also distinguished by its location at a major research university and, as such, hosts the largest number of graduate and undergraduate students.

The loss of C-Mod would:

- Eliminate studies of tritium fuel retention and power flow to the wall and divertor in ITER-relevant edge conditions, which have potentially serious consequences for ITER.
- Eliminate ITER-relevant tests of thermal, particle and momentum transport with radio frequency heating and current-drive techniques in plasmas with the ITER-like characteristics of ions and electrons coupled at the same temperature through collisions, no core external momentum-drive, and high-pressure edge conditions.
- Compromise development of ion cyclotron and lower hybrid RF capabilities for controlled plasma heating and edge current drive essential for advanced tokamak scenarios in ITER and future burning plasma facilities.



What Research Opportunities Would Be Lost

<u>DIII-D</u> is the best equipped – in terms of diagnostics, heating and control systems – and most flexible tokamak –in terms of shaping capability – in the world. It has an outstanding record of contributing to plasma science and technology, and to the development of advanced scenarios for tokamak operation that offer the possibility for ITER to achieve its goals at reduced plasma current. Its capabilities have been enhanced, and this excellent program is expected to continue producing essential information for the advancement of science and the magnetic fusion program.

The loss of DIII-D would:

- Eliminate a major world-class program that contributes to understanding turbulent transport, fast ion instabilities, pedestal and divertor physics, and mode stabilization.
- Eliminate further development of a high β, high bootstrap current, “steady-state” plasma and of hybrid operating scenarios for ITER.
- Cede the U.S. position of leadership in electron cyclotron current drive for current profile and MHD stability control.

What Research Opportunities Would Be Lost

NSTX is the most powerful and most fully diagnosed low-aspect-ratio magnetic fusion experiment in the world, with extremely flexible shaping capability and the ability to access ultra-high plasma β values. The facility provides an operational regime for key science theories to be tested and confirmed, providing understanding for tokamak fusion devices in general.

The loss of NSTX would:

- Eliminate not only the U.S. leadership position in the world for device capability and research on spherical tokamaks, but also eliminates the U.S. ability to guide and contribute to spherical torus research at the “proof-of-principle” level.
- Eliminate numerous important experiments such as Bernstein wave current drive, plasma start-up in a proof-of-principle scale experiment, ultra-high β operation, and fast ion measurements.
- Eliminate U.S. leadership in high β tokamak research, and the U.S. independence to pave the path to the future strategic option of constructing a Component Test Facility based on the spherical torus.

Recommendation

In a February 2005 report titled Ò*The Knowledge Economy: is the United States losing its competitive edge?,*Õthe Task Force on the Future of American Innovation Òdeveloped a set of benchmarks to assess the international standing of the U.S. in science and technology. These benchmarks in education, the science and engineering workforce, scientific knowledge, innovation, investment and high-tech economic output reveal troubling trends across the research and development spectrum. The U.S. still leads the world in research and discovery, but our advantage is rapidly eroding, and our global competitors may soon overtake us.Ó

In the particular area that is the subject of our report, that of the scientifically interesting and broadly important topic of magnetic fusion energy research, our Panel finds that the U.S at present holds a position of international strength and leadership. The next major magnetic fusion research facility will be the offshore burning plasma experiment, ITER.Ê Fostered by the recent decision over its ITER site, interest in ITER is rapidly growing in the international research community. The loss of any of the three major U.S. toroidal fusion facilities would fundamentally jeopardize the ability of U.S. researchers to perform relevant fusion research, and thus would undermine the current U.S. position of international excellence.

Recommendation

The three major U.S. magnetic fusion facilities ĞC-Mod, DIII-D, and NSTX Ğrepresent a massive investment of talent, intellect, and finances in tackling the key issues of toroidal confinement. Each of these facilities has made seminal contributions to the development of toroidal confinement and to the fundamental science and technology that undergird it. The wealth of discoveries and the generation of knowledge made possible by the three coordinated U.S. facilities has enabled the U.S. to be an effective presence among the larger foreign programs involved in ITER. Premature closure of one of these three major facilities would seriously compromise the effectiveness of the U.S. fusion program internationally and also the U.S. ability to advocate future proposals for advanced performance scenarios that could lead to a more economically competitive high-power-density fusion system.

Recommendation

The Panel’s recommendation is that the three major United States toroidal magnetic fusion facilities continue operation to conduct important unique and complementary research in support of fusion energy sciences and ITER.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DISCUSSION

* Photo/Image provided courtesy of the Naval Research Laboratory.

NRL spectroheliograph image of the sun, taken aboard Skylab in 1973, using the extreme ultraviolet radiation from ionized helium, 304 Angstom wavelength.