THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

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Dear Dr. Orbach:

At its meeting on September 17, 2002, you asked the National Research Council's Burning Plasma Assessment Committee (BPAC) to report in December on two aspects of its charge and to comment on whether the United States should reenter the negotiations on the International Thermonuclear Experimental Reactor (ITER), an international burning plasma experiment.[1] This interim report, submitted in response to that urgent request, addresses only two aspects—the importance of a burning plasma experiment for fusion energy and the scientific and technical readiness to undertake a burning plasma experiment—and offers advice on entering ITER negotiations. The issues discussed here will be amplified in the course of the study, and the final report will address the wider aspects of the burning plasma issue and their relation to the fusion energy science program. In particular, considerations of the broader scientific value of burning plasma science and of the Fusion Energy Science Advisory Committee's (FESAC's) proposed dual-track strategy for developing a burning plasma experimental program are deferred to the committee's final report. With these caveats, the committee offers the following recommendations:

Subject to the conditions listed below, the committee recommends that the United States enter ITER negotiations while the strategy for an expanded U.S. fusion program is further defined and evaluated.

A strategically balanced fusion program, including meaningful U.S. participation in ITER and a strong domestic fusion science program, must be maintained, recognizing that this will eventually require a substantial augmentation in fusion program funding in addition to the direct financial commitment to ITER construction.

The fusion program strategy should include cost estimates and scenarios for involvement in ITER, integration with the existing fusion science program, contingency planning, and additional issues as raised in this letter. The United States should pursue an appropriate level of involvement in ITER, which at a minimum would guarantee access to all data from ITER, the right to propose and carry out experiments, and a role in producing the high-technology components of the facility, consistent with the size of the U.S. contribution to the program.

[1] The United States was a member of the ITER team prior to its withdrawal in 1998. Following consecutive budget cuts in the fusion program (from $365 million in FY1995 to $225 million in FY1997) and its restructuring from a schedule-driven development strategy into a science-driven program in 1996, the U.S. Congress mandated withdrawal from ITER following the completion of the ITER Design Activity. Since 1998, the remaining ITER partners have continued with the development of a redesigned and improved ITER machine, and negotiations on the choice of a site and other important decision milestones are well under way.

Overview

The study of the science and technology of burning plasmas is a critical missing element in the restructured program of the Department of Energy's Office of Fusion Energy Science (referred to in this report as the U.S. fusion program). The recent report from the National Research Council's Fusion Science Assessment Committee (FUSAC) noted that experimental investigation of a burning plasma remains a grand challenge for plasma physics and a necessary step in the development of fusion energy.[2] In light of the need to accomplish that step and of the significant advances over the last decade in the understanding of magnetically confined plasmas and in improved designs for burning plasma experiments, the committee recommends that the U.S. fusion program participate in a burning plasma experiment.

During the last decade, by focusing its reduced resources on plasma science, the U.S. fusion community has achieved notable advances in understanding and predicting plasma performance—particularly in the field of plasma theory and experimental work on small and intermediate physics experiments. These advances are documented in detail in the FUSAC report, which noted the "remarkable strides" in fusion science research. Of particular note is the ongoing effort to develop a fundamental understanding of the complex turbulent processes that govern the confinement of hot plasmas in magnetic fields. This effort has resulted in new theoretical models, large-scale computer simulations, new diagnostic techniques, and quantitative comparisons between theory and experiment. Application of these models gives added confidence to projections for the operation of a burning plasma experiment. There also has been progress in the understanding and control of a new class of large-scale magnetohydrodynamic (MHD) plasma instabilities, the neoclassical tearing mode, which has been a significant concern for the burning plasma regime. Progress in predicting, controlling, and mitigating fast plasma terminations has significantly reduced concerns about unacceptable electromechanical stresses in the proposed experiment. Experiments, both current and planned, and theory are bringing attractive advanced tokamak regimes with high pressure and self-driven currents closer to reality. These tokamak operating regimes may lead to a more economically attractive concept for a fusion reactor.

The progress made in fusion science and fusion technology increases confidence in the readiness to proceed with the burning plasma step. A modest reduction in mission and the incorporation of advanced design elements from the fusion science community have resulted in a more attractive proposal for ITER. These changes have reduced the estimated cost of such an experiment and allowed the development of advanced tokamak features in the burning plasma regime. The proposed design requires less extrapolation from present experiments, and the operating regime resides safely below established limits in plasma density, pressure, and current, making operational projections much more reliable. However, an additional and important goal of the burning plasma experiment is to explore operational regimes that are not so predictable and where instabilities are expected to arise in the self-heated burning plasma. Finally, experience with prototype components built as part of the design preparations for the ITER and IGNITOR experiments has increased confidence in the ability to build, assemble, and operate a burning plasma experiment.

Here, the committee offers two caveats: First, the fusion community is aging and has long range demographic problems. New people are required if the nation is to expand its efforts and make the program endure. The necessity of attracting graduate students and postdocs into the program requires the program to have a strong university-based component. Second, a technology program without a strong science base, or a science program without a strong technology base, will leave the United States in a position where it cannot build effectively on the developments coming from more advanced programs abroad. In its 1993 report *Science, Technology, and the Federal Government: National Goals for a New Era*, the National Academies' Committee on Science Engineering and Public Policy (COSEPUP) said that the United States should be among the leaders in all major areas of science, and should maintain clear leadership in some of these areas so that it can take advantage of breakthroughs wherever they take

[2] National Research Council, Fusion Science Assessment Committee (FUSAC)*An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, , National Academies Press, Washington, D.C., 2001.

place.[3] The United States was arguably the world leader in fusion science and technology two decades ago—a position recognized by the 1995 fusion report from the President's Committee of Advisors on Science and Technology (PCAST).[4] The FUSAC report also recognized the long standing U.S. leadership in this field and pointed to its traditional strengths, stated that the U.S. program has traditionally been an important source of innovation and discovery for the international fusion energy effort, and pointed to a distinguishing feature of the U.S. program—its goal of understanding at a fundamental level the physical processes governing observed plasma behavior. The FUSAC report concluded that the science funded by the Office of Fusion Energy Science was easily on a par with the quality in other leading areas of contemporary physical science. However, owing to the subcritical utilization of domestic facilities, the near elimination of the technology program, and the inability to mount major new experiments building on improved scientific understanding, the U.S. fusion community could be at risk of dropping out of even the "among the world leaders" group. The largest and most capable facilities are now outside the United States. Many of the critical confidence-building steps that must precede the construction and operation of a burning plasma experiment, particularly the technology steps, have taken place in other countries, including those that are members of the ITER team, albeit with U.S. participation prior to its withdrawal from the program.

ITER Negotiations

There is a clear consensus among members of the fusion community who participated in the 2002 Snowmass meeting, the subsequent FESAC panel, and FESAC itself that the United States should now seek to join the ITER negotiations. As a result of what it learned from presentations at its first two meetings, the committee agrees with that proposal. Furthermore, no matter how one envisions a future development path for fusion energy, the fusion community has concluded, and the committee agrees, that a burning plasma experiment is a necessary and the next immediate step. The committee recommends that the United States should negotiate a level of involvement consistent with the size of the U.S. contribution to the program, which at a minimum should guarantee access to all data from ITER, the right to propose and carry out experiments, and an appropriate role in producing the high-technology components of the facility.

Relation to Existing Fusion Energy Science Program

Conclusion No. 6 from the 2002 Snowmass Fusion Summer Study states that a strong base science and technology program is needed to advance essential fusion science and technology and to participate effectively in, and benefit from, the burning plasma effort.[5] All presenters to the committee indicated the need to maintain a strong core program, illustrated by the FESAC recommendation that a strong core science and technology program is essential to the success of the burning plasma effort, as well as to the overall development of fusion energy.[6] Further, the FUSAC report noted that a fusion research program must investigate a range of confinement approaches and that it is the combined progress made in science and engineering that will determine the pace of advancement toward the energy goal. If the United States joins ITER, the committee concludes that it will be essential to maintain a strong base-science program as a companion to such a major facility program. The theoretical understanding of the conditions required for a burning plasma will evolve as new data come in from existing tokamaks and

[3] National Academy of Sciences, National Academy of Engineering, Institute of Medicine (SEM), Committee on Science Engineering and Public Policy (COSEPUP), *Science, Technology, and the Federal Government: National Goals for a New Era*, National Academies Press, Washington D.C., 1993.
[4] Panel on Fusion Energy Research, President's Committee of Advisors on Science and Technology, Office of Science and Technology Policy, Executive Office of the President, *The U.S. Program of Fusion Energy Research and Development*, Washington, D.C., July 1995, available online at <http://www.ostp.gov/PCAST/fusionenergypub.html>.
[5] Snowmass 2002 Fusion Summer Study, Executive Summary, available online at <http://web.gat.com/snowmass/exec-summary.pdf>.
[6] Fusion Energy Science Advisory Committee (FESAC) Panel Report, *A Burning Plasma Program Strategy to Advance Fusion Energy*, September 2002, available online at <http://www.ofes.fusion.doe.gov/More_HTML/FESAC/Austinfinal.pdf>.

advanced-concept machines and from large-scale computer simulations. New, advanced diagnostics will be developed. All of these will be needed to optimize the scientific value of participation in a burning plasma experiment. In addition to supporting the burning plasma experiment, the U.S. fusion program must continue a parallel effort focused on developing the scientific base for attractive fusion reactor concepts. This effort will need to include fundamental plasma science, exploration of innovative confinement concepts, and theory and computation development. The relationship between the core program and the proposed burning plasma program will be addressed in more detail in the committee's final report.

The current ITER cost estimate of $5 billion does not include such items as R&D to develop needed instrumentation, nor does it include a contingency. FESAC indicated that the ITER construction effort would require additional funding of $100 million per year from the United States over a 10-year program (with the actual expenditure profile matching the construction profile). In addition, FESAC reported that the core fusion science program should not be decreased to provide funds for ITER but should be increased. In addition to the costs of construction, support activities that are not included in the construction budget will have to be funded. Additional funding for burning-plasma-related support activities and augmentation of the core science program were estimated by FESAC and yourself at $50 million to $100 million per year, without elaboration.

While there has not been time to examine this estimate in detail, the committee recognizes that a strategically balanced fusion program must contain two indispensable components: a strong domestic fusion science program and meaningful U.S. participation in ITER. Maintaining such a program will necessitate a very large increase in total funding of the order presented to the committee. An expanded fusion program would be needed to participate in ITER, maintain the necessary activities in the domestic program, and position the United States to reap the maximum benefit from the scientific and technological progress that will come from both the ITER program and the DOE's Office of Fusion Energy Science core program. The impact of such resource needs on the fusion science program has not been considered in detail, but the additional sum is a significant fraction of the existing fusion energy science program support, and impact would be inevitable. The committee notes that to proceed beyond an ITER-scale machine to some sort of demonstration project would require additional facilities. The committee has not yet addressed the overall DOE burning plasma program and its related elements but will do so in its final report.

Moving to Reenter Negotiations for ITER Participation

You have indicated there is some urgency to proceed to negotiations for participation if the United States is to have influence on allocation of responsibilities among partner states in the ITER program. The Director of the Office of Science and Technology Policy also told the committee that the United States soon must decide whether to enter ITER negotiations. The committee recommends that the United States enter ITER negotiations while the strategy for an expanded U.S. fusion program is further defined and evaluated.

The committee recommends that in entering the ITER negotiations, the Department of Energy should take several actions:

1. Develop an estimated total cost of full participation in the ITER program, using standard U.S. costing analysis methods and considering the potential full scope. (The committee was pleased to learn that a preliminary review of the construction costs has been delivered to the Department of Energy and considers this is an important first step in understanding the potential costs of the ITER program for the United States.)
2. Analyze several scenarios for U.S. involvement.
3. Assess the impacts of U.S. participation in ITER on the core fusion science program, including opportunities to increase international leverage in the core program as well.

4. Develop other options for a burning plasma experiment in case ITER construction is not approved by the negotiating parties.
5. Establish an independent group of experts to support the U.S. ITER negotiating team on scientific and technical matters.

Having made these observations and presented its recommendations, the committee next addresses two aspects of its charge—the importance of a burning plasma experiment for fusion energy and the scientific and technical readiness to undertake a burning plasma experiment.

Scientific and Technological Value and Interest

Introduction

Fusion energy holds out the promise of providing a significant part of the long-term environmentally acceptable energy supply. At the center of all schemes to make fusion energy is a plasma—an ionized gas which, like the center of the Sun, is heated by fusion reactions. The plasma is said to be burning when more than half of the plasma heating comes from fusion. All fusion reactors require a burning plasma. The key challenge is to confine the hot and dense plasma while it burns. Two experiments in the 1990s—the Tokamak Fusion Test Reactor (TFTR) in Princeton and the Joint European Torus (JET) in the United Kingdom—obtained significant power from deuterium-tritium fusion reactions. However, no experiment has yet entered the burning plasma regime, and the physics in this self-heated regime remains largely unexplored. A burning plasma experiment would address for the first time the scientific and technological questions that all fusion schemes must face. This is the crucial element missing from the world fusion energy science program.

Scientific advances in the 1990s significantly improved several related magnetic-confinement configurations. For example, advanced tokamaks, reversed-field pinches, spherical tori, and stellarators all have advantages, and all have made significant progress in the last decade. The discovery that confinement can be enhanced by suppressing turbulence and then finding regimes compatible with steady-state operation have enhanced the reactor potential of these configurations. It is too early to predict which configuration has the best potential for becoming a commercial fusion reactor. However, tokamaks are the most advanced magnetic-confinement configuration. They alone have established a scientific basis that can be projected to burning conditions with reasonable confidence, although new challenges to plasma stability and control may yet arise in the self-heated regime. A tokamak-based burning plasma experiment should produce scientific understanding and technological developments of general use for a wide range of possible future fusion configurations. Thus a balanced fusion program—a burning plasma experiment plus the OFES core program—that develops the science and technology of a range of fusion confinement configurations and of burning plasma is essential.

In this section, the committee explores the critical motivations for the proposed experiments by summarizing the importance of a burning plasma experiment for fusion energy sciences and technology and for fusion as an energy source.

Scientific Importance

Burning plasmas at near reactor scale will present new scientific challenges that must be explored and understood to enable the development of fusion energy. In addition to the ongoing research on plasma confinement and heating, as has been previously noted in many reviews of the U.S. fusion program, this goal requires experimental research on a burning plasma, where the plasma is mainly self-heated by fusion reaction products. Fundamentally, this requirement to investigate the burning regime is due to the nonlinear behavior of magnetically confined plasma at high temperature and pressure, a behavior that in turn may be modified by the alpha-particle heating. In addition, burning plasmas used for energy production will be significantly larger in volume than present experiments, affecting the plasma confinement, and they may therefore be expected to show new phenomena and changes in previously studied behavior.

The expected new phenomena in burning plasma are due to fusion-generated fast alpha particles, which will be the dominant heat source for the plasma. The fusion rate increases approximately as the square of the plasma pressure. This nonlinear heating will combine with the turbulent confinement of the plasma to modify the plasma equilibrium and behavior. In addition, the alpha particles can collectively generate fluctuations—for example, energetic particle modes and Alfvénic modes—affecting the confinement of the alpha particles themselves or, possibly, the rest of the plasma. The fluctuations could, therefore, allow alpha particles to escape without heating the plasma. The alpha particles stabilize some MHD modes and induce new unstable modes. Thus the nonlinear behavior is exceedingly complex. While these fluctuations have been studied experimentally using externally generated energetic ions, the space and energy distribution of these ions and their anisotropy are significantly different from those of fusion-generated alpha particles, modifying the fluctuations and their impact on the fast ion confinement.

Extrapolation from present experiments to the effective size of a full energy-producing reactor entails substantial uncertainty, which can, however, be reduced by studying a burning plasma experiment. To obtain sufficient confinement for burning, the effective plasma size (physical size divided by ion magnetic-gyroradius) must be substantially increased, by increasing the actual plasma size or the magnetic field strength. This increase in effective size at high plasma temperature is predicted to modify many phenomena already studied in existing experiments, such as the saturation of turbulence-generated transport and the onset of macroscopic (tearing) instabilities. These phenomena can determine the plasma pressure that can be confined and thus the level of fusion power produced. The large effective size may significantly change the spectrum of unstable Alfvénic fluctuations, generating turbulence and increasing alpha-particle losses. Regimes with these parameters are not accessible in present experiments.

A burning plasma experiment is necessary to further understand and develop the operating strategies needed for fusion energy, simultaneously satisfying many constraints presently studied separately. An energy-producing fusion system must not only generate sufficient fusion power, it must also exhaust the helium ash and absorb the generated energy at the walls of the device without deleterious effects. In addition, to lead to an efficient, robust energy-production system, the reactor should operate at high plasma pressure in steady state. These issues will be more challenging at the larger scale of a burning plasma and in the presence of nonlinear alpha-particle heating.

Technological Importance

Depending on its scale, a burning plasma experiment could offer an early opportunity to begin development of essentially all technologies needed for a fusion reactor. These include components and systems unique to fusion's energy goal; plasma technologies such as heating, current drive, and fueling systems; hardened diagnostics; and superconducting coils of unprecedented size and energy. In addition, by operating safely, reliably, and within the structural code requirements used by the nuclear industry, a burning plasma experiment can demonstrate the favorable safety characteristics of a fusion reactor.

A burning plasma experiment could provide the opportunity to test and evaluate blanket designs. The breeding blanket—that is, a nuclear system that creates tritium via interaction of the fusion-produced 14 MeV neutrons with lithium—is a key fusion nuclear technology. Fusion reactors must operate with more tritium produced and recovered than is burned. While blanket designs using low-activation materials and compatible coolants have been developed and would seem to promise net tritium production, their performance can only be evaluated by operation with an extended source of 14 MeV neutrons in a reactor-like environment. A burning plasma experiment provides the opportunity to evaluate the thermomechanical performance, the tritium breeding ratio and extraction process, and the plasma compatibility of near-full-scale test blanket modules. However, the fluence in the burning plasma experiments under consideration will be too low to explore the reactor-relevant lifetime characteristics of such test blanket modules.

The behavior and integrity of materials in a fusion system are of great importance to the long-term viability of fusion energy. The high flux of energetic neutrons poses a serious materials problem that will require substantial testing, some of which may be done on a burning plasma experiment and the rest of which may require a separate materials test facility. This will be discussed further in the final report.

Burning plasma experiments would contribute to developing the technology for tritium processing. Most of the fuel injected in a fusion reactor will not be burned in a single pass. Unburned fuel will be continuously transported to the plasma edge, where it must be collected, separated from impurities, and then reinjected. The technology for doing this exists at a small scale, but the demonstration of an integrated steady-state reprocessing capability by a burning plasma experiment would show that the technology exists at the scale needed for a reactor. A related issue is to show that the tritium inventory in a fusion reactor can be kept to an acceptably low level.

Burning plasma experiments will need to develop high-heat-flux components and will serve as a testbed in which to evaluate the performance of the components in a reactor-like fusion environment. The heat loads on divertor or limiter targets in burning plasma experiments will be comparable to those expected in a reactor. This requires application of state-of-the-art high-heat-flux technology using materials that satisfy requirements of tritium retention, safety, structural integrity, lifetime, and plasma compatibility.

In a fusion reactor, it is critical that the first wall and high-heat-flux components, as well as ancillary components such as RF heating antennas and diagnostics, can be remotely repaired with tolerable downtime for maintenance. The scientific success of a burning plasma experiment will be critically dependent on the successful use of these tools to minimize lost experimental time due to component failure. Prototypes of the tools exist; a burning plasma experiment will provide an integrated demonstration of their reliability and effectiveness.

Scientific and Technical Readiness to Pursue a Burning Plasma Experiment

Overview

This section summarizes the present state of scientific and technical readiness to undertake a burning plasma experiment. It relies on the results of the recent major burning plasma studies—FESAC 1997 ITER physics basis review,[7] ITER final design report,[8] and the Snowmass studies of 1999[9] and 2002.[5] The committee accepts the summary conclusions of these studies and used the information contained in them to formulate its conclusions on the scientific and technical readiness. The committee also accepts that the scientific and technical bases for proceeding with a burning plasma experiment have been established. A number of key criteria that characterize scientific and technical readiness for a burning plasma experiment are detailed below.

Scientific Readiness

1. *There must be a sufficient level of confidence in confinement projections. The present level of uncertainty in these projections is acceptable.*

Reaching the burning plasma regime depends critically on the rate at which energy is lost from the plasma. This energy loss rate can be inferred on the basis of confinement scaling, nondimensional scaling, flux-surface-averaged transport modeling, and three-dimensional

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[7] Fusion Energy Sciences Advisory Committee (FESAC) Panel Report, *Review of the International Thermonuclear Experimental Reactor, Appendix D*, April 18,1997, Washington D.C., available online at <http://wwwofe.er.doe.gov/more_html/FESAC/Appendices.pdf>.

[8] ITER Council, *Final Report of the ITER Engineering and Design Activities*, July 2001, Vienna, available online at <http://www.iter.org/ITERPublic/ITER/Summary_FDR.pdf>.

[9] Proceedings of the 1999 Snowmass Fusion Summer Study, available online at <http://www.ap.columbia.edu/SMproceedings/>.

plasma turbulence simulations. The observed energy loss rates from large tokamaks (from >1,000 discharges in eight tokamaks[10]) can be successfully fit using appropriate nondimensional discharge scaling parameters. This technique accurately projects energy loss rates in existing tokamak experiments and has been used successfully in designing new tokamaks. An extrapolation of the energy loss rate by a factor of less than 3 is required to go from the best confinement in present large tokamaks to ITER. Alternatively, existing large tokamaks can simultaneously match all appropriate nondimensional parameters projected for ITER discharges except for the size parameter (the ratio of the plasma radius to the ion gyroradius). The scaling of the energy loss rate with this size parameter is inferred by comparing discharges in different tokamaks with the remaining nondimensional parameters held fixed. Extrapolation by a factor of 3.6 in the size parameter is then required to project the energy loss rate in ITER. Both methods project that ITER will meet (or exceed) its goal of producing 10 times more power via fusion reactions in the plasma than the input power used to heat the plasma.

Of course a major feature of a burning plasma experiment is the possibility of new nonlinear interactions between the heating from the fusion-produced fast alpha particles and the plasma equilibrium. It is possible that such interactions could alter the confinement properties of the plasma. This possibility might make it difficult to extrapolate knowledge from present experiments to the new burning plasma regime. For this reason, one goal of conducting a burning plasma experiment is to test the validity of just such projections of confinement and transport into this heretofore unexplored regime.

There is also a continuing effort to improve our understanding of energy and particle transport in tokamaks. Transport models based on analyses of plasma instabilities and three-dimensional simulations of turbulence can now infer ion thermal diffusion in the plasma core (although the understanding of profiles in the pedestal at the plasma edge remains qualitative and semiempirical), and they have been extensively benchmarked against experimental results. The realistic simulations of plasma turbulence that form the basis of these models are the result of successful algorithm development and advances in computer hardware. These simulations provide detailed information about the mechanisms responsible for the loss rates of heat, momentum, and plasma particles. Taken together, these advances provide an acceptable level of confidence in projecting the performance of the proposed burning plasma experiments and predict adequate performance of the redesigned ITER experiment.

2. *The present operational boundaries and other constraints, including limits on plasma pressure (i.e., "beta") and current, must be and are sufficiently well understood to proceed.*

There is a limit to the plasma density that is proportional to the plasma current. This limit is known empirically, and the ITER design will operate safely below this limit. Tokamak operation is also constrained by limits on the plasma pressure and current. Such limits, which can be calculated using MHD theory, can now be avoided through control of the plasma pressure and current. The ITER base program will operate safely within these limits. Experiments are also planned to explore the boundary of this stable regime with the goal of further expanding the burning-plasma operating regime.

Within this stable operating regime, there is another class of instabilities, called neoclassical tearing modes, that can degrade plasma performance. These instabilities depend strongly on the dissipation and transport properties of the plasma, and the theory for them is still in development. While this stability boundary cannot yet be predicted with precision, an important recent development is the discovery of a method to stabilize the plasma using localized, microwave driven currents. This stabilization technique is understood theoretically. The planned addition of microwave-based current-

[10] ITER Physics Expert Groups, *Nuclear Fusion* **39**, 2175 (December 1999).

drive capabilities in ITER is expected to provide a means of stabilizing these modes should they become significant.

3. *There must be sufficient confidence that other abnormal events can be avoided or mitigated. While there is such confidence, further R&D is needed to develop plasmas that present less stringent heat loads to plasma-facing components.*

Burning plasma experiments are designed to safely handle abnormal events such as disruptions should they occur. Recent experiments have shown that disruptions can be avoided. If excursions beyond this safe operating regime do occur, new techniques, such as the injection of argon gas, can be used to quench the plasma and avoid damage to the device as a result of electromechanical stresses and runaway electrons. Further experiments are needed to confirm that "thermal quench" damage to the walls and/or divertor plates can simultaneously be avoided.

There is an instability of the plasma edge, known as the edge localized mode, that can cause large, repetitive heat loads on plasma-facing components that could severely limit their lifetime. While a predictive understanding of these modes is still in development, it is encouraging to note that experiments have now identified regimes with good plasma performance and with either significantly reduced edge mode amplitudes or no edge localized modes at all. These results raise confidence that the deleterious effects of this edge localized mode will be avoidable. However, further R&D is still required, both to better understand these edge localized modes and to develop reliable methods to mitigate peak heat loads without degrading burning plasma performance.

4. *There must be sufficient confidence that the required plasma purity can be obtained, including helium removal and the inhibition of impurity influx from the first wall and divertor. There is such confidence.*

The introduction of impurities into the plasma, either as helium from the fusion reaction or from sputtered first-wall material, can substantially increase the energy confinement time required to maintain a burning plasma. Experiments have demonstrated that the helium ash and other impurities can be successfully removed from the plasma by extracting gas formed when the plasma recombines at the divertor plates. Experiments and modeling of the edge plasma and scrape-off layer increase confidence that the production of impurities and their influx into the plasma can be maintained within acceptable limits, although the physical models for the plasma edge region need further refinement.

5. *Techniques must be—and are—available to adequately characterize and evaluate most of the important parameters in a burning plasma. Important factors include adequate diagnostic access, diagnostic operation in a neutron environment, and remote maintenance of measurement instruments.*

The scientific evaluation of a burning-plasma experiment requires reliable measurement of key quantities with good spatial and temporal resolution in a high neutron environment. There is confidence that most of these measurements can be made with adequate precision, assuming adequate flexibility in the design of the device. Topics for further R&D as part of the burning plasma program include measurements of the distribution of fusion alpha particles, the plasma current profile, and the properties of the plasma turbulence.

6. *Plasma control techniques must exist that are adequate to produce and evaluate burning plasma physics and to explore steady-state advanced operational regimes. Such techniques have been developed.*

There is good confidence that the proposed burning plasma experiment will achieve the key goal of studying the burning plasma regime—that, is that the self heating from the fusion reaction will exceed the heating from external power sources—based on operation in a conventional high-confinement (H-mode) regime. While many of the important burning plasma scientific issues can be addressed in this regime, the ability to operate in high-performance ("advanced tokamak") regimes will be an important step in the successful realization of an attractive fusion power plant. Recent success in creating nearly fully noninductive discharges at high plasma pressure has expanded the range of operating parameters for a burning plasma experiment, so that—at least potentially—ITER could also study this preferred, advanced-tokamak regime of operation. The control of plasma initiation, shape, and discharge evolution has been demonstrated and is understood. There is an adequate knowledge of techniques for plasma fueling and exhaust control, as well as an understanding of methods for auxiliary heating and current drive. The active stabilization of MHD instabilities and the avoidance and mitigation of abnormal events are sufficient to conduct a burning plasma experiment, but more research is needed in this area.

Experiments in auxiliary heated tokamaks have demonstrated that the operational limits described above can be significantly extended through control of the plasma pressure and current profiles. The experimental program for ITER includes exploration of this advanced-tokamak regime, in which control of the pressure and current profiles is complicated significantly. This complexity arises from the nonlinear interactions between the pressure profile, the heating source (proportional to the square of the plasma pressure), the self-driven current (proportional to the pressure gradient), and the turbulent transport (which depends on the pressure, the pressure gradient, and the current profile). The plasma control tools required to begin studies of this regime are largely in hand. However, further R&D on fueling the central plasma (for pressure profile control) and control of plasma rotation (for stabilization of resistive wall modes) is needed. Further R&D is also required to develop methods to control plasma transport (including control of internal transport barriers) and the interaction of RF heating sources with fusion alpha particles in the advanced tokamak regime. Research should also continue in the area of electron density and density-profile control and magnetic feedback of resistive wall modes.

Technical Readiness

From the FESAC 1997 ITER physics basis review[11] and the Snowmass studies of 1999[9] and 2002[5], the committee has identified six criteria that define readiness to create and study burning plasmas. These criteria have now been met. A few criteria, described below, remain unfulfilled, but ongoing research can be expected to adequately address them. It is worth noting that many of the confidence-building steps mentioned here were accomplished by researchers outside the United States at fusion research facilities in Europe, Japan, and the Russian Federation, with U.S. participation during the ITER Engineering Design Activity and prototype testing prior to U.S. withdrawal.

1. *It must be possible to manufacture and assemble the necessary components, including the required magnetic field coils, the vacuum vessel, the divertor, and the first-wall components. There is sufficient confidence that this can be done.*

The R&D conducted over the past 5 years gives confidence that the proposed devices can be built. Prototype components have been successfully built for all major systems on ITER, including full-vacuum vessel segments, and remote fabrication and repair schemes have been tested. The R&D effort on the ITER central solenoid gives confidence that these coils can be built. Testing has revealed that minor modifications of the ITER solenoid coil design are needed to meet the field requirements with a good engineering safety margin. The fabrication techniques have been demonstrated with prototypes.

[11] Fusion Energy Sciences Advisory Committee (FESAC) Panel Report, *Review of the International Thermonuclear Experimental Reactor*, April 18,1997, Washington D.C., available online at <http://wwwofe.er.doe.gov/more_html/FESAC/ITER.Report.pdf>

2. *It must be possible for major components to operate within the design requirements in the expected nuclear environments. There is sufficient assurance on this issue.*

The design of the ITER superconducting coils includes the required protective shielding. Further R&D is needed for some diagnostics, including those sited in high-neutron-flux areas and those requiring transparent optical materials. Further research is also required to develop beam-based fluctuation diagnostics.

3. *It must be possible to design and build plasma-facing components that can handle the anticipated heat flux, particle flux, and mechanical stresses, including during disruptive discharge termination. Prototypes have been built, and much progress has been made.*

Prototype designs of plasma-facing components have been tested for normal heat flux conditions, and the mechanical designs accommodate the projected disruption forces. Significant research into the use of both carbon-based materials and refractory metals (tungsten and molybdenum) has been completed successfully. More research will be required to qualify these materials for use in a fusion device. Mitigation techniques for disruption heat loads have been developed that assure sufficient lifetime with respect to erosion. The one exception is the plasma edge localized mode typical of the highest-performance plasmas. These modes cause rapid and repetitive deposition of energy to the plasma-facing components. The resulting erosion greatly shortens component lifetimes. Experiments have shown some degree of mitigation by plasma shaping and edge density control with little loss of confinement. Further research is required to mitigate the effects of these edge modes.

4. *It must be possible to handle the required tritium throughput safely. Tritium inventory depends strongly on the choice of plasma-facing materials, and further research is needed to increase the operational duty cycle of the device. There is growing confidence on this issue.*

The ITER safety analysis shows that the device meets fusion safety standards and will not require an evacuation plan extending beyond the site boundary. Previous experiments on both JET and TFTR have safely handled substantial amounts of tritium. Separate experiments have resulted in the development of techniques to handle the amounts of tritium required.

Plasma-facing components made of carbon (the divertor plates) present special problems in that eroded and redeposited carbon can absorb large amounts of tritium. The projected tritium retention in this eroded carbon can, in turn, increase machine downtime as a result of the need to remove the trapped tritium. Unless a method can be identified to reduce this tritium trapping in carbon by one or two orders of magnitude, it is unlikely that carbon will be an acceptable material. Refractory metals are an alternative divertor plate material with no tritium retention problems, although possible surface melting during severe disruption thermal quenches is a concern. Further research in this area is required to develop an improved understanding of the migration of eroded, redeposited carbon in the plasma periphery, to explore means of reducing tritium trapping, and to consider alternative materials.

5. *The required remote maintenance for a burning plasma experiment must be possible. This has been demonstrated.*

Remote handling of in-vessel components has been done on JET. Prototypes of major systems for a burning plasma experiment have been designed and tested. Full-size prototype remote handling devices have been fabricated and shown to be capable of performing the required operations. Optimization of the design is continuing.

6. *There must be adequate fueling, heating, and current drive techniques to control and explore burning plasmas. These are being worked on, and progress is being made.*

Injection of frozen deuterium-tritium pellets is a proven fueling method, but additional R&D is needed to extrapolate to the size and density required for a burning plasma experiment. Techniques for heating with ion cyclotron and electron cyclotron radiation are well established. Electron cyclotron radiation is also used for plasma profile control. Lower hybrid and fast wave ion cyclotron radiation have been used for current drive. Techniques to heat plasmas with high-energy, negative-ion neutral beams have also been developed. Various plasma heating and current drive systems will require antennas, wave guides, and radio frequency mirrors near the plasma. The choice of structural materials, insulators, and guard materials for these structures is still being optimized.

Conclusion

The committee agrees with the conclusions of the recent studies—namely, that the scientific and technical bases for proceeding with a burning plasma experiment have been established. Recent theoretical and experimental progress in understanding and controlling tokamak plasmas and progress in developing burning-plasma-relevant technology provide added confidence that a burning plasma experiment can be carried out.

Summary

In summary, the committee finds that the progress made in fusion science and fusion technology increases confidence in the readiness to proceed with a burning plasma experiment—the next step for the U.S. fusion program and one the committee has found to be of great scientific and technological value. The committee recommends that, subject to the conditions listed herein, the United States enter ITER negotiations while the strategy for an expanded U.S. fusion program is being further defined and evaluated.

Sincerely,

John Ahearne
BPAC Co-Chair

Raymond Fonck
BPAC Co-Chair