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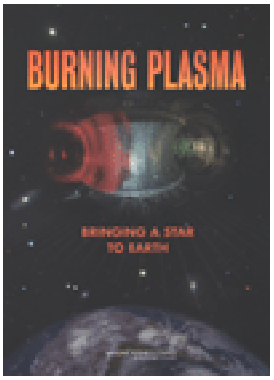

Burning Plasma: Bringing a Star to Earth

Burning Plasma Assessment Committee, Plasma Science Committee, National Research Council

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BURNING PLASMA

BRINGING A STAR TO EARTH

Burning Plasma Assessment Committee

Plasma Science Committee

Board on Physics and Astronomy

Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
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Cover: The Tokamak Test Fusion Reactor (TFTR) was a fusion experiment at the Princeton Plasma Physics Laboratory that achieved one of the world's first partially burning plasmas in the 1990s. Image courtesy of Princeton Plasma Physics Laboratory.

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Preface

The goal of achieving a sustained thermonuclear fusion burn capable of generating power in some future reactor has been a long-term research goal for the United States and the global research community. In the past decade great strides have been made toward that goal, leading the fusion research program to a decision point—is it ready to take the step of executing a burning plasma experiment, and how should that step be taken?

Given the considerable federal investment over several decades, the fusion program has rightly been the subject of many reviews and assessments—by the National Research Council (NRC), the Department of Energy's Fusion Energy Sciences Advisory Committee, and the President's Council of Advisors on Science and Technology—and has also been the subject of congressional review. Most recently the question has been whether the United States should include a burning plasma experiment—one in which at least 50 percent of the energy needed to sustain the fusion reaction is generated from within the plasma—in the Department of Energy's magnetic fusion program as operated by the Office of Fusion Energy Sciences (OFES). A burning plasma experiment is a key scientific milestone on the road to the development of fusion power.

The Burning Plasma Assessment Committee was established by the National Research Council under the Board on Physics and Astronomy with oversight and guidance from the Plasma Science Committee in July 2002 at the request of DOE's Office of Science.[1] The committee was charged with assessing (1) the importance

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[1] The establishment of an NRC committee on a burning plasma experiment was also written in to legislation under consideration by Congress at the time of the committee's establishment.

of a burning plasma experimental program, (2) the scientific and technical readiness to undertake a burning plasma experimental program, and (3) the plan for the U.S. magnetic fusion burning plasma experimental program. It was asked to make recommendations on the program strategy aimed at maximizing the yield of scientific and technical understanding as the foundation for the future development of fusion as an energy source (see Appendix A for the full text of the task).

The Burning Plasma Assessment Committee was established to conduct the latest of several NRC studies that have considered the direction of the U.S. fusion program over the past decade. Both the 1995 report *Plasma Science: From Fundamental Research to Technological Applications*[2] and the 2001 report of the Fusion Science Assessment Committee (FUSAC)[3] provided vital background for the Burning Plasma Assessment Committee in carrying out this study. *Plasma Science* concluded that many opportunities for fundamental scientific exploration were missed because of the then-schedule-driven energy development mandate of the fusion energy program. The report also recommended that, to aid the development of fusion and other energy-related programs, the Department of Energy should provide increased support for basic plasma science. The FUSAC study concluded that "a program organized around critical science goals will also maximize progress toward a practical fusion power source."[4]

The third item of the committee's task was to provide "an independent review and assessment of the plan for the U.S. *magnetic fusion* burning plasma experimental program" (emphasis added; see Appendix A). None of the inertial confinement fusion (ICF) programs are considered in this report since they are not part of the magnetic fusion program and, with the exception of the small, heavy ion program, are not part of a program aiming toward the use of fusion for commercial energy purposes. The major work of DOE's large program in ICF is the study of high energy density physics using implosions driven by energy deposition from focused laser beams and plasma pinches. A major facility will be the National Ignition Facility at the Lawrence Livermore National Laboratory, as well as the Z machine at Sandia National Laboratories. Much of the ICF work is done as part of the nuclear weapons work in the National Nuclear Security Administration, a section of the Department of Energy. A small program is beginning to explore the use of heavy ions for ICF energy deposition.

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[2] National Research Council, *Plasma Science: From Fundamental Research to Technological Applications*, Washington, D.C.: National Academy Press, 1995.

[3] National Research Council, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, Washington, D.C.: National Academy Press, 2001.

[4] National Research Council, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, Washington, D.C.: National Academy Press, 2001, p. 2.

The membership of the Burning Plasma Assessment Committee was designed to bring together experts in fusion science, plasma science, and other areas (see Appendix G) to consider the charge. At the committee's first meeting, Raymond Orbach, director of DOE's Office of Science, requested an interim report by the end of 2002, addressing two aspects of the charge—the importance of a burning plasma experiment for fusion energy, and the scientific and technical readiness to undertake a burning plasma experiment—and, in particular, to provide advice on the question of U.S. reentry into the negotiations for the International Thermonuclear Experimental Reactor (ITER).[5] Issued on December 20, 2002, the interim report[6] recommended that the United States reenter the ITER negotiations with a view to full participation in the experiment. Following publication of the report, President Bush announced that the U.S. government would rejoin the negotiations, and a U.S. team has since become active.[7]

In the context of possible U.S. reentry into the ITER negotiations, the interim report offered some preliminary findings and conclusions with respect to the importance and readiness issues, but left much of the charge to the committee unaddressed. After completing its interim report, the committee focused on the remainder of its charge and, most importantly, on the consideration of a strategy for "maximizing the yield of scientific and technical understanding as the foundation for the future development of fusion as an energy source" (see Appendix A).

In addressing its task the committee considered questions relevant to the charge that included, but were not limited to, the following:

- What are the important scientific and technical problems to be addressed in the burning plasma experimental program?
- To what degree will the solutions further the development of fusion energy in magnetic-confinement systems generally or in tokamaks specifically?
- What is the scientific interest in these problems?
- To what degree can individual problems be investigated in smaller, less costly experiments, and to what degree does satisfactory understanding

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[5] ITER will be a burning plasma experiment based on the tokamak concept—the leading magnetic-confinement fusion configuration, whose name comes from the Russian word for a toroidally (or doughnut) shaped magnetic field. ITER is expected to be larger than existing tokamaks, with a major radius of 5 to 8 m, and is expected to use superconducting magnets to confine the hot plasma.

[6] The text of the Burning Plasma Assessment Committee's interim report is reproduced in Appendix E of this report and is available online at http://books.nap.edu/openbook/NI000487/html/index.html.

[7] The negotiations to start the ITER project are being attended by the European Union, Russia, Japan, China, South Korea, Canada, and the United States.

depend on integration of the phenomena in a single burning plasma experiment?

- What are the merits and limitations of the principal realizations currently proposed for a burning plasma experiment, and to what degree can each realization address the problems identified in the answer to the first question?
- Does the plan for a burning plasma experimental program envision sufficient diagnostics, theory, and technology support to generate good understanding of the problems to be investigated?
- What are the implications of a given experiment for the future development of the program?
- Will the burning plasma experimental program be well integrated with the rest of the U.S. fusion program?
- Will it be well integrated with international efforts in fusion research?

The committee's task was a challenging one. In considering the questions listed above and in approaching the execution of its charge, the committee received important input from the fusion community and others—at its formal meetings[8] and via an e-mail solicitation to the plasma community and a town meeting held at the annual meeting of the American Physical Society's Division of Plasma Physics. The committee extends its gratitude to the community for this input, and in particular thanks the organizers of and participants in the Fusion Workshop held in Snowmass, Colorado, in July 2002. The committee commends all of those involved in the Snowmass project for providing a valuable technical assessment of the options for achieving a burning plasma experiment.

In particular, the committee expresses its appreciation to the following individuals for their contributions to its work and the completion of this report: Bruno Coppi, Stephen Dean, Robert Goldston, Robert Hirsch, Karl Lackner, Michael Mauel, Dale Meade, Gerald Navratil, Stewart Prager, Marshall Rosenbluth, Ned Sauthoff, and Ronald Stambaugh. The committee also expresses its deepest gratitude to Michael Moloney, the NRC study director for this committee, and to Donald Shapero, director of the Board on Physics and Astronomy, and Thomas O'Neil, chair of the Plasma Science Committee, who put tremendous and productive effort into defining the scope of this study with colleagues on the Plasma Science Committee and at the Department of Energy. Finally, we thank Timothy Meyer, who, after Michael Moloney left, took over and successfully managed the

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[8] Agendas for the committee's four meetings are provided in Appendix B.

difficult task of the final steps in the National Research Council's review process and brought this report through to publication.

In presenting this report, we would like to thank our colleagues on the committee. The diversity of the committee's areas of expertise was its greatest strength, leading to many difficult questions being asked in our open and closed discussions. The committee's findings, conclusions, and recommendations are presented with the hope that, as the nation faces financially challenging times, this report will help inform the difficult decisions that must be taken to support an important field of science. It behooves the fusion community and those who support its work to develop a prioritized strategy to provide a realistic framework for the advancement of a science that has the potential to lead to an exciting new energy source.

John F. Ahearne, *Co-chair,* and Raymond Fonck, *Co-chair*
Burning Plasma Assessment Committee

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Jack Conner, United Kingdom Atomic Energy Agency,
Ronald C. Davidson, Princeton University,
W. Kenneth Davis, Bechtel Corporation (retired),
Val L. Fitch, Princeton University,
Cary B. Forest, University of Wisconsin at Madison,
Harold K. Forsen, National Academy of Engineering,
T. Kenneth Fowler, University of California at Berkeley,
William Happer, Princeton University,
David Meyerhofer, University of Rochester, and
Marshall N. Rosenbluth, University of California at San Diego.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti (Lucent Technologies) and Charles F. Kennel (University of California at San Diego). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Summary

Fusion energy holds the promise of providing a significant part of the world's long-term, environmentally acceptable energy supply. At the center of all schemes to make fusion energy is a plasma—an ionized gas that, like the center of the Sun, is heated by fusion reactions. The plasma is said to be burning when alpha particles from the fusion reactions provide the dominant heating of the plasma. All fusion reactors require a burning plasma. The key challenge is to confine the hot and dense plasma while it burns.

The search for a means of controlling thermonuclear fusion has been based on the study of high-temperature plasma physics; it has led to the development of both magnetic and inertial confinement systems to contain the plasma. Carried out in the United States under the sponsorship of the Department of Energy's (DOE's) Office of Fusion Energy Sciences (OFES), fusion research (referred to herein as the U.S. fusion program) has made remarkable progress in recent years in understanding and controlling turbulence and instabilities in fusion plasmas, which in turn has led to improved plasma confinement. Theory and modeling are now able to provide useful insights into instabilities and thus to guide experiments. Experimental diagnostics can extract useful information about the processes occurring in high-temperature plasmas.

The successes of the U.S. fusion program can be attributed to its science-centered approach, aimed at three goals:

- To advance plasma science in pursuit of national science and technology goals;
- To develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and
- To pursue fusion energy and technology as a partner in the international effort.[1]

Experiments that have been carried out on the suite of U.S. and foreign tokamaks have been successful in significantly advancing the scientific and technical knowledge base for fusion. Research in innovative and alternate magnetic fusion concepts is contributing to an understanding of how to design, implement, and control future fusion devices. Theory and simulation have contributed significantly to progress in understanding the behavior of fusion plasmas—for example, in the area of turbulence and nonlinear physics. The university-scale efforts within the fusion program have enabled the advances in the fusion effort and provided personnel for the program as a whole. The question now is, What is the next major step for the U.S. fusion effort?

It is widely agreed in the plasma physics community that the next large-scale step in the effort to achieve fusion energy is to create a burning plasma—one in which alpha particles from the fusion reactions provide the dominant heating of the plasma necessary to sustain the fusion reaction. The objective of creating a burning plasma is to understand the physics of the confinement, heating, and stability of burning plasmas as well as to explore the technical problems connected with the development of a power-producing fusion reactor. A burning plasma experiment is a key scientific milestone on the road to the development of fusion power.

The Burning Plasma Assessment Committee was charged with analyzing and reporting on the following topics: the importance of a burning plasma experiment, the readiness of the U.S. fusion community to undertake a burning plasma experiment, and the DOE's plan for a burning plasma experimental program. The committee was also asked to make recommendations on the program strategy that would maximize the output of such a program for the future development of fusion as an energy source. Because the committee's charge was limited to the consideration of magnetically confined burning plasmas, none of the inertial confinement fusion programs are considered in the report.

The development of fusion as a source of power is a multidecade enterprise. It

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[1] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

is subject to many unknowns—both technical and societal—that are beyond the scope of this committee's charge. Indeed, the DOE has not yet established a clear program strategy for fusion (and hence did not present one to the committee), in part because the plans for an international burning plasma experiment have been in flux for the past few years. The committee's goal is, nevertheless, to define a program approach that will optimize the near-term productivity of the U.S. fusion program and position it for development in the future at levels deemed appropriate at that time. With this task in mind, the committee offers here a short précis of the main elements of this report and then presents its recommendations and their rationale.

- A burning plasma experiment is critically needed to advance fusion science. The committee is pleased that the U.S. government has rejoined the International Thermonuclear Experimental Reactor (ITER)[2] negotiations, which the committee expects will be successful. If the negotiations are not successful, progress toward fusion energy will require moving ahead with some other kind of international burning plasma experiment.
- Undertaking a burning plasma experiment cannot be done on a flat budget. If the United States is interested in the long-term goal of fusion as a source of economical, sustainable energy and not only in the ITER effort, the nation needs a science program based on some of the existing facilities; a technology program; a computation, simulation, and theory program; and a university program. At a minimum, to capture the benefits of a burning plasma experiment, an augmentation of the U.S. program covering all of the U.S. ITER construction and operating costs would be required in the near term.
- If negotiations proceed successfully, the fusion science program will move ahead with the ITER endeavor. In doing so, the fusion community should focus on the opportunities that this development will present and accept limitations on the level of activity possible within reasonable budget constraints. It is necessary to recognize that some of today's facilities will have to be shut down over time and that not all alternate concepts are affordable. Priorities will be set. Although this committee was not tasked to set them, it

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[2] ITER will be a burning plasma experiment based on the tokamak concept—the leading magnetic-confinement fusion configuration, whose name comes from the Russian word for a toroidally (or doughnut) shaped magnetic field. ITER is expected to be larger than existing tokamaks, with a major radius of 5 to 8 m, and is expected to use superconducting magnets to confine the hot plasma. The negotiations to start the ITER project are being attended by the European Union, Russia, Japan, China, South Korea, Canada, and the United States.

does recommend that the community take part in a real prioritization process for the fusion program. The Office of Fusion Energy Sciences must take the lead and bring the community to consensus.

On the basis of its own assessments and deliberations, the committee concludes that the progress made in fusion science and fusion technology has increased overall confidence in the readiness to proceed to the burning plasma step, allowed the development of more reliable operational projections, and reduced the estimated cost of such an experiment. An important goal of the burning plasma experiment is to explore operating regimes that are not so predictable and that are likely to give rise to instabilities in the self-heated burning plasma. Such experimentation will make critical contributions to the understanding of how to optimize future directions in fusion research and development.

The committee makes the following specific recommendations and observations:

- **The United States should participate in a burning plasma experiment.**

Participation in a burning plasma experiment is a critical missing element in the U.S. fusion program. The scientific and technological case for adding a burning plasma experiment to the U.S. fusion science program is clear. There is now high confidence in the readiness to proceed to the burning plasma step because of the progress made in fusion science and fusion technology. Progress toward the fusion energy goal requires this step, and the tokomak is the only fusion configuration ready for implementing such an experiment.

- **The United States should participate in the International Thermonuclear Experimental Reactor (ITER) project. If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced U.S. fusion science program.**
- **The United States should pursue an appropriate level of involvement in the ITER project, 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.**
- **If the ITER negotiations fail, the United States should continue, as soon as possible, to pursue the goal of conducting a burning plasma experiment with international partners.**

Of the alternatives proposed for U.S. participation in a burning plasma experiment, ITER, with the United States as a significant partner, is the best choice. The ITER design is the most mature and is also sufficiently conservative to provide great confidence in achieving burning plasma conditions while being flexible enough to test critical advanced tokamak operating regimes in near-steady-state burning plasma conditions. It also allows tests of several fusion-relevant technologies. Participation by the United States in ITER also very effectively leverages the U.S. investment in its own fusion science program.

The pace of the ITER program will be decided by the participants through the negotiating process. The U.S. component will be settled as the negotiations proceed and as procurement packages are assigned and construction preparations commence. These negotiations will determine the U.S. financial contribution to ITER construction as well as the role for and demands on the U.S. program as an ITER partner. Once a U.S. commitment is made to help construct and to participate in ITER, fulfilling this commitment will necessarily become the highest priority in the U.S. fusion science program. It is reasonable to expect that the larger the commitment, the more U.S. participation in the ITER program will be able to meet the nation's interest in progressing toward fusion energy.

A preliminary and successful review of the ITER construction costs has been conducted by DOE.[3] This is an important first step in understanding the potential costs of the ITER program for the United States. Furthermore, DOE is carrying out an analysis of the various work packages of primary interest to the U.S. fusion science program, and it has engaged the fusion community in this effort by establishing the Burning Plasma Program Advisory Committee and holding an ITER forum for community input. These, too, are welcome developments.

Notwithstanding the goodwill of all of the negotiating parties and the significant progress made to date, the ITER negotiations could conceivably fail. In that case, in order to progress with the development of fusion energy, it would be necessary to look for an alternative approach to a burning plasma experiment, and that most likely would become an international collaboration. In such a scenario, the United States should reassess its options before developing an alternative strategy. Because a burning plasma experiment is a key step on the necessary scientific critical path toward fusion energy, any delays in realizing such an experiment—such as failure in the ITER negotiations—would necessarily delay the domestic program's ability to address and understand fusion science questions that must be answered before practical fusion power can be developed.

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[3] *Department of Energy Assessment of the ITER Project Cost Estimate*, November 2002. Available online at http://fire.pppl.gov/doe_iter_lehman.pdf. Accessed December 12, 2003.

- **A strategically balanced U.S. fusion program should be developed that includes U.S. participation in ITER, a strong domestic fusion science and technology portfolio, an integrated theory and simulation program, and support for plasma science. As the ITER project develops, a substantial augmentation in fusion science program funding will be required in addition to the direct financial commitment to ITER construction.**

Although the scale of U.S. participation in the ITER program is as yet undetermined, it is clear that the U.S. fusion effort requires a strategically balanced program in the context of participation in ITER. In structuring the U.S. fusion program with participation in ITER, it will be important to maintain the fusion science program as a diversified one that includes science, technology, theory, simulation, and experimentation conducted using the domestic and the international suite of current and planned tokamak and non-tokamak facilities.

In this context, the committee has not found particularly useful the common characterization of the U.S. fusion program as a "base program" and a burning plasma program. All of the elements of the U.S. fusion program—advancing plasma science; developing fusion science, technology, and plasma confinement innovations; and pursuing fusion energy science and technology as a partner in the international effort—are essential and coupled.

The ITER program should not be the only determinant in the effort to achieve a new balance for the entire U.S. fusion program. For instance, a technology program without a strong science base, or a science program without a strong technology base, will leave the United States unable to build effectively on the developments coming from more advanced programs abroad as well as from the ITER program. In addition, the pursuit of fusion as an attractive energy source requires the investigation of critical plasma physics and stability issues, which are discussed in more detail later in this report (see the section entitled "Scientific Importance of a Burning Plasma for Fusion Energy Science and the Development of Fusion Energy" in Chapter 2). Many of the scientific and technical issues of importance to the long-range development of the fusion program will be best addressed by non-burning-plasma facilities with tokamak and non-tokamak machines. Thus, the U.S. fusion program must continue a domestic effort in parallel with the ITER project focused on developing the scientific base for promising fusion reactor concepts.

The committee emphasizes the need for a robust program of theory and simulation, coupled with experimental verification, to maximize the yield of scientific and technical understanding from a balanced fusion program. Theory and simulation are essential components in gaining understanding of large-scale fusion systems and have contributed significantly to progress in understanding the behavior of fusion plasmas—for example, in the area of turbulence and nonlinear physics. Going forward, a program in theory and simulation must rely on a marriage of advances in experimental fusion science, information technology, plasma science, applied mathematics, and future developments in software.

The internationalization of fusion research is increasing along with the development of the ITER project. It is important that some of the pre-ITER research and development in the U.S. fusion science program be coordinated with international partners and the ITER process. The U.S. tokamak programs are already loosely integrated with major facilities in the European Union and Japan through the International Tokamak Physics Activity, which identifies and promotes areas of cross-fertilization and comparative experiments. The international effort should not be limited only to ITER activities, or indeed to collaborations on the large tokamaks in the global fusion portfolio. International partnerships for developing alternative fusion configurations have been and will continue to be important.

- **The U.S. fusion science program should make a focused effort to meet the need for personnel who will be required in the era of the burning plasma experiment. This effort should have the following goals: to attract talent to the field; to provide broad scientific and engineering training, specialized training, and training on large devices, as required; and to revitalize the fusion workforce.**

The recruitment, training, and retention of scientific and technical talent are crucial elements of the U.S. fusion program. The success of the U.S. fusion effort will depend on strong programs in plasma and fusion science. Among the continuing and future roles of universities are those of maintaining the workforce supply and serving as research centers that can generate and nurture new scientific and technological ideas, as well as leverage extensively the latest knowledge from other fields of science. The roles that university programs play in meeting needs for personnel and in providing new ideas and training opportunities can be expected to continue throughout the era of the burning plasma experiment and farther along the path to practical fusion energy. In addition, postdoctoral research programs at the national facilities provide critical advanced training in detailed fusion science issues. The technology component of the U.S. program will be the training ground for the fusion engineers and for those developing the industrial skills needed for the future.

- **Undertaking a burning plasma experiment cannot be done on a flat budget.**

As with any vibrant research program, the development of a scientifically and programmatically balanced program for fusion energy research and development must be matched with a credible and achievable funding plan. The plan should have a multiyear focus and fit within federal spending constraints. However, a flat budget for the OFES will inevitably lead to decay in facilities and a decline in research opportunities and will virtually guarantee that the United States will not gain the desired benefits from its investment. Such a reduced effort in the critical activities that the U.S. fusion community needs to pursue will increase the risk that the United States will play a following rather than a leading role in the ITER scientific program and the development of fusion energy.

A funding trajectory that avoids these risks would provide the support to capture the long-term benefits of joining the international ITER collaboration while retaining a strong scientific focus on the long-range goal of the domestic program. This approach would support fusion research as a vibrant and exciting enterprise with opportunities for attracting the best young talent into the field, as well as increasing the connections of fusion research to the other fields of science and engineering in academia. As important, such an approach will position the U.S. contingent in the ITER program to be leaders in significant fractions of the overall program.

- **Although active planning has been undertaken by the U.S. fusion community in recent years, the addition of so major a new element as ITER requires that, to ensure the continued success and leadership of the U.S. fusion science program, the content, scope, and level of U.S. activity in fusion should be defined through a prioritized balancing of the program. A prioritization process should be initiated by the Office of Fusion Energy Sciences to decide on the appropriate programmatic balance, given the science opportunities identified and the budgetary situation of the time. The balancing process also could be guided by multiyear budget planning that projects funding growth and should involve significant community input. The prioritization process should be organized with three elements of the fusion program in mind:**

  —To advance plasma science in pursuit of national science and technology goals;
  —To develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and
  —To pursue fusion energy science and technology as a partner in the international effort.

These program elements are indeed the three goals of the U.S. fusion program as outlined by the OFES in 1996. The committee affirms these elements as substantive and appropriate for a strategically balanced program.

The merit of any of the U.S. fusion science program activities now under way or envisioned does not mean that every activity can or even should be supported unconditionally. Any funding scenario that can be reasonably expected will necessitate deciding the relative priority of activities to pursue at any given time. The choice of which opportunities to pursue—and which program activities not to pursue—must be determined by the usual federal government process, advised by the fusion community and cognizant of international fusion efforts.

A rigorous evaluation of the U.S. fusion program priorities should be undertaken by the OFES with broad-based input from the fusion community. This priority-setting process should be guided by the objective of maintaining a balanced program, as discussed in this report, and it should result in a clear, ordered list of activities to be pursued. Such a list would identify those areas of science and technology that either have the greatest uncertainty or that promise the greatest impact for the future of the fusion program.

As with the planning done for other areas of science such as for high-energy physics, the fusion community should identify and prioritize the critical scientific and technology questions to address in concentrated, extended campaigns. A prioritized listing of those campaigns, with a clear and developed rationale for their importance, would be very helpful in generating support for their pursuit, while also requiring the development of a clear decision-making process in the fusion research community.

There are many unknowns as the fusion community embarks on this great scientific challenge. The elements required for the long-term health and vitality of this part of the U.S. research enterprise are not entirely clear, but this report strives to provide guidance for balancing the U.S. fusion program through an elucidation of the key scientific, technical, and programmatic issues that need to be addressed in the coming years as it enters the burning plasma era. What is clear is that whatever strategy is adopted, it should be flexible, innovative, and inclusive in achieving the required balance for success.

Having concluded that the United States is ready to take the next critical step in fusion research, the committee recommends the implementation of a burning plasma experiment through participation in the ITER program as part of a strategically balanced U.S. fusion program. The opportunity for advancing the science of fusion energy has never been greater or more compelling, and the fusion community has never been so ready to take this step.

1

Next Steps for the Fusion Science Program

INTRODUCTION

The search for a means to control thermonuclear fusion has led to the development of magnetic and inertial plasma confinement systems and to the study of high-temperature plasma physics in general. Fusion research, carried out in the United States under the sponsorship of the Department of Energy's (DOE's) Office of Fusion Energy Sciences (OFES) and referred to herein as "the U.S. fusion program,"[1] has made remarkable progress in recent years and has passed several important milestones. A large element in this program is that focused on the science of magnetic fusion, in which hot fusion plasmas are confined by large magnetic fields.

Significant progress has been made in understanding and controlling turbulence and instabilities in high-temperature plasmas; this in turn has led to improved plasma confinement. Theory and modeling are now able to provide useful insights into turbulence and to guide experiments. Experimental diagnostics can extract detailed information about the processes occurring in high-temperature plasmas. It is widely perceived in the plasma physics community that the next

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[1] The committee recognizes that the U.S. fusion program includes substantial efforts in inertial fusion energy. Considering these elements of the program was not part of the committee's charge. However, no inference should be drawn from the omission of this part of the OFES program from the committee's discussion.

large-scale step in magnetic fusion research and high-temperature plasma physics is to create a burning plasma—one in which alpha particles from the fusion reactions provide the dominant heating of the plasma. The objective of doing so is to understand the physics of the confinement, heating, and stability of a burning plasma as well as to explore the technical problems connected with the development of a power-producing fusion reactor. A burning plasma experiment is a key scientific milestone on the road to the development of fusion power.

The first mildly burning plasma experiments were achieved in the 1990s at the Tokamak Fusion Test Reactor (TFTR) in the United States and at the Joint European Torus (JET) in the United Kingdom. The plasmas in these experiments generated up to 16 MW of fusion power for about 1 s; 80 percent of this power was in the form of 14 MeV neutrons, which escaped from the plasma, and 20 percent was in the form of 3.5 MeV charged alpha particles (helium nuclei) that were confined within the plasma. These alpha particles heat the plasma through Coulomb collisions with the other particles within the plasma—the fraction of transient alpha-particle heating in TFTR was about 5 percent and in JET about 15 percent. Nevertheless, in both cases alpha-particle-induced heating of electrons near the plasma core was clearly measured. These experiments began the exploration of the burning plasma regime.

Several strongly burning plasma experiments have been proposed, including the International Toroidal Reactor (INTOR), the U.S. Compact Ignition Tokamak (CIT), the U.S. Burning Plasma Experiment (BPX), the Italian IGNITOR experiment, the International Thermonuclear Experimental Reactor (ITER), and, most recently, the U.S. Fusion Ignition Research Experiment (FIRE) (see Appendixes C and F for additional information on proposed experiments and fusion reactor concepts). The experimental goal in each of these experiments is to reach a plasma state in which the alpha-particle self-heating is the dominant energy source for the plasma.[2] The creation of such plasmas is a necessary but not sufficient condition for the development of a practical energy-producing magnetic fusion power plant.

The study of the science and technology of burning plasmas is a critical missing element in the OFES program. The recent report from the National Research Council's Fusion Science Assessment Committee (FUSAC)[3] noted that experi-

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[2] The fusion-produced alpha-particle heating is considered dominant when it is sufficient to strongly impact the plasma pressure and temperature profiles. This occurs when the alpha heating is comparable to or greater than the external heating source. Thus, the terms "dominant heating source" and "half the energy input" are used interchangeably throughout the text to indicate the required alpha-particle heating contribution for a burning plasma experiment.

[3] National Research Council, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, Fusion Science Assessment Committee (FUSAC), Washington, D.C.: National Academy Press, 2001 [hereafter referred to as NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*].

mental investigation of a burning plasma remains a grand challenge for plasma physics and a necessary step in the development of fusion energy. In light of the need to accomplish that step and in view of the significant advances over the past decade in the understanding of magnetically confined plasmas and in improved designs for burning plasma experiments, the committee recommended in its interim report that the U.S. fusion program participate in a burning plasma experiment.[4]

During the past decade, the fusion community has achieved notable advances in understanding and predicting plasma performance—particularly in comparing the results of theoretical and numerical calculations with the results of experiments 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. The application of these models gives added confidence to projections for the operation of a burning plasma experiment.

Progress has also been made 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.

The incorporation of advanced design elements from the fusion science and technology community has resulted in more attractive proposals for the burning plasma experiment. These changes have reduced the estimated cost of such an experiment and have allowed the investigation of advanced tokamak features in the burning plasma regime. The designs require less extrapolation from present

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[4] National Research Council, *Letter Report of the Burning Plasma Assessment Committee*, Burning Plasma Assessment Committee (BPAC), Washington, D.C.: National Academies Press, 2002. (The text of this interim report is reproduced in Appendix E and is available online at http://books.nap.edu/openbook/NI000487/html/index.html.)

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, where instabilities are expected to arise in the self-heated burning plasma. Undertaking a burning plasma experiment within the U.S. fusion program is a great challenge to the fusion community and to the program itself. It is a step that requires careful strategic planning—a requirement that led to detailed consideration of such a strategy through "the Snowmass process"[5] and lengthy deliberations of the DOE's Fusion Energy Sciences Advisory Committee (FESAC). In addition, DOE charged the Burning Plasma Assessment Committee to conduct an assessment of the importance of a burning plasma experiment, an analysis of the readiness to undertake a burning plasma experiment, and an assessment of DOE's plan for a burning plasma experimental program. The committee was also asked to make recommendations on the program strategy to maximize the output of such a program for the future development of fusion as an energy source. (See Appendix A for the complete charge to the committee.)

The present report answers this charge. Chapter 1 describes the context of the entire discussion and lays out a description of the committee's reasoning; the chapter concludes with recommendations and guidance. Chapters 2 and 3 then describe in more detail the compelling scientific importance of and readiness for a burning plasma experiment, respectively. Chapter 4 discusses the overall structure of the nation's fusion program in light of the general comments made in Chapter 1.

The issues raised in the later chapters are summarized in the following sections of this chapter as a synopsis of the rationale behind this committee's findings, which motivated a number of well-defined conclusions. These findings and conclusions are the foundation for the recommendations presented at the end of this chapter.

This report focuses on the charge to the committee by assessing the scientific readiness for and benefits from participation in a burning plasma experiment. It is important to note that many additional issues and activities are critical to achieving practical fusion energy through magnetic confinement, but they are outside the purview of this committee. These include issues such as the qualification of

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[5] The Snowmass process engaged the U.S. fusion community in a technical assessment of the options for U.S. participation in a burning plasma experiment. The process culminated in a 2-week community conference in July 2002. The outcomes of this assessment were provided to the DOE's Fusion Energy Sciences Advisory Committee (FESAC) for its consideration with respect to the direction of the U.S. fusion program.

nuclear materials for long-life operation under high neutron fluences, the development of low-activation materials, the qualification of near-full-scale power technologies such as chamber components, high duty factor testing, and fuel breeding and management. The modeling and testing of the effects of fusion-produced neutrons on materials constitute an area of considerable scientific challenge and interest in itself. The proposed burning plasma experiment will allow some initial examination of several of these fusion technology issues, but their more complete development for practical fusion energy will require consideration at future dedicated facilities beyond ITER. This report focuses on the merits of the proposed experiment to elucidate the scientific and technological issues of a burning plasma.

PREPARING FOR A BURNING PLASMA EXPERIMENT

Although developing any energy source is a long and difficult task, the international fusion community has concluded that the critical next step toward fusion energy is to build a facility capable of achieving a burning plasma.[6] Demonstrating a burning plasma is the experiment necessary for continuing to develop the scientific and technological understanding to proceed toward the development of controlled fusion energy.

A number of experiments, ranging from a reactor-scale device using superconducting magnets, to compact, high-field copper-magnet devices, have been considered for implementing a burning plasma experiment (see Appendix C for a discussion of the three currently proposed burning plasma projects—ITER, FIRE, and IGNITOR). On the global scale the greatest effort has been put into realizing the International Thermonuclear Experimental Reactor, an international facility that is designed to demonstrate the scientific feasibility of fusion as an energy source and to develop and test key features of the technology that will be required for a fusion power plant.[7] A cutaway figure of the device is shown in Figure 1.1.

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[6] Several reports have considered this issue (see Appendix D for some fusion community efforts in this regard). The National Research Council has also addressed the subject of burning plasmas, saying, most recently, "(The) experimental investigation of a burning plasma remains a grand challenge for plasma physics and a necessary step in the development of fusion energy" (NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, p. 53).

[7] Before its withdrawal in 1998, the United States was a member of the ITER team. Following consecutive budget cuts in the U.S. fusion program (from $365 million in FY 1995 to $225 million in FY 1997) and its restructuring from a schedule-driven development strategy into a science-driven program in 1996, the U.S. Congress mandated withdrawal from the ITER program following the completion of the ITER Engineering 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 decisions are well under way.

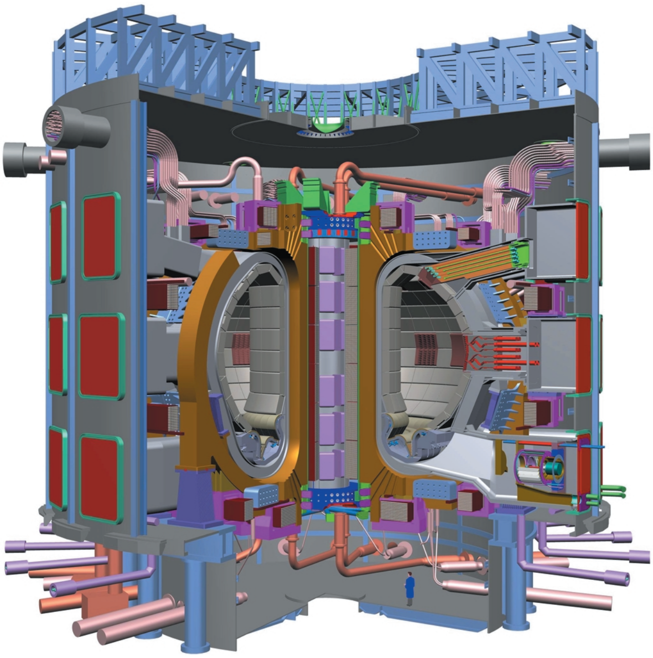

FIGURE 1.1 Schematic of the International Thermonuclear Experimental Reactor (ITER), which is under development. (A person is shown for scale in the lower-right region near the center.) Courtesy of ITER.

The ITER project has benefited greatly from the expertise and scrutiny of fusion-plasma researchers throughout the world. The present design is the result of a decade of effort, which included one major redesign that lowered the anticipated cost by a factor of 2 by reducing the size and eliminating some of the capability to test fusion power components and technologies. The engineering design of ITER is well developed, and prototypes for many of the systems have been built. ITER provides excellent opportunities to address key physics issues. ITER has been designed to accommodate a range of heating and current drive technologies and to have the most complete set of plasma diagnostics of the three currently proposed burning plasma experiments. The long pulse capability, the range and flexibility of heating and current drive technologies, and the extensive diagnostic set provide the capability to explore and evaluate advanced, steady-state operating regimes. In addition, the present ITER design would demonstrate integrated operation of some of the important technologies for fusion power.

The U.S. fusion community has asserted that a burning plasma experiment is an essential milestone on the road to practical fusion energy and has identified its readiness to proceed to ITER as the desired platform for investigating burning plasma behavior (see Appendix D regarding recommendations of the fusion community). The community's near unanimity is based on important advances in understanding the behavior of large-scale hot plasmas. These advances come from experiments on a host of tokamaks around the world, on theory and computer simulations to understand and predict the results of experiments, and on the development of technologies that have made advanced facilities and diagnostics available.

With the foregoing assertion of the community in mind, the U.S. fusion program was considering reentering the negotiations on the ITER program when this committee was established. At the committee's first meeting, on September 17, 2002, Raymond Orbach, director of the DOE Office of Science, asked the committee to report, by December 2002, on two aspects of its charge and to comment on whether the United States should reenter the ITER negotiations. The resulting interim report (see Appendix E) was issued on December 20, 2002, in response to that urgent request.

The interim report, expanded upon in the later chapters of this report, makes clear what can be learned from such a burning plasma experiment and why the overall understanding achieved in the past decade makes a burning plasma experiment achievable. These findings are summarized below.

Scientific Value and Interest

Fusion energy holds the promise of providing a significant part of the world's long-term, environmentally acceptable energy supply. At the center of all schemes to make fusion energy is a plasma—an ionized gas that, like the center of the Sun, is heated by fusion reactions. A burning plasma experiment would address for the first time the scientific and technological questions that all magnetic fusion schemes must face. The scientific importance of such an experiment is discussed in Chapter 2 and summarized here. In addition to enabling the next steps in research on plasma confinement and heating, a burning plasma experiment will present new scientific challenges with a plasma that is mainly self-heated by fusion reaction products. The nonlinear behavior of magnetically confined plasmas at high temperature and pressure, a behavior that in turn may be modified by the alpha-particle heating, is of fundamental interest. 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.

An extrapolation from present experiments to the effective size of an energy-producing reactor entails substantial uncertainty, which can, however, be reduced by studying a burning plasma experiment. The increase in effective plasma size at high plasma temperature is predicted to modify many phenomena that can determine the level of fusion power produced in a reactor. Understanding these effects is not feasible in the smaller-scale[8] fusion experiments that are available to the scientific community today.

In particular, it can be expected that a burning plasma experiment, owing to its unique plasma parameters and its ability to study these issues in the burning state, will make critical contributions to understanding the following:

- Plasma behavior when self-sustained by fusion (burning),
- Fusion-plasma turbulence and turbulent transport,
- Stability limits to plasma pressure,
- Control of a sustained burning plasma, and
- Power and particle exhaust.

In addition to its scientific importance to fusion energy science, a burning plasma experiment may also make contributions to plasma science and science in general. Basic plasma physics is the study of fundamental processes in the plasma state of matter and is relevant to a variety of fields, including space plasmas, industrial plasmas, astrophysics, and fusion. A burning plasma experiment is designed specifically to investigate the burning plasma state and cannot replace experiments that are purpose-built to directly address the broader set of basic plasma issues. However, a burning plasma experiment and the scientific program that leads to and supports it may make useful contributions to the basic understanding of plasmas on issues such as these:

- Magnetic field line reconnection,
- Plasma turbulence,
- Abrupt plasma behavior, and
- Energetic particles in plasmas.

In considering the potential for even broader impact, the committee notes that progress in plasma physics, and fusion-plasma physics in particular, can lead to progress in other subfields of physical science. A burning plasma experiment will likely lead to progress in new regimes. There will undoubtedly be unexpected discoveries. Only a few examples of such connections are mentioned here. For

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[8] "Smaller scale," in the context of this report, should be interpreted as meaning smaller than the ITER scale.

instance, burning plasmas will generate the highly energetic ions and large temperature gradients that characterize many astrophysical systems and provide the opportunity to study enhanced transport under these more realistic conditions. In addition, a burning plasma experiment may offer a chance to learn about self-organization of a complex physical system with strong drivers and weak constraints, which occurs in many astrophysical, space, and geophysical settings. Self-organization is characterized by phenomena on small spatial scales acting in concert to produce phenomena on large scales.

Technological Value and Interest

Depending on its scale, a burning plasma experiment could offer the opportunity for beginning the 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 divertors; heating, current drive, and fueling systems; hardened diagnostics; remote handling and maintenance capabilities; and superconducting coils of unprecedented size and energy. A burning plasma experiment will provide an integrated demonstration of the reliability and effectiveness of these technologies. In addition, by operating safely, reliably, and within the structural code requirements used by the nuclear industry, a burning plasma experiment can demonstrate some of the favorable safety characteristics of fusion power.

A burning plasma experiment could provide the opportunity to test and evaluate blanket designs—the blanket being the physical system surrounding the hot plasma; it provides shielding and absorbs fast neutrons, converts the energy into heat, and produces tritium. A 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. A burning plasma experiment provides the first opportunity to evaluate test blanket modules.

A burning plasma experiment will 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 demonstration of an integrated steady-state reprocessing capability in a burning plasma experiment would show that the technology can be extrapolated to 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.

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. Burning plasma experiments will need to develop high-heat-flux components and will serve as testbeds in which to evaluate the performance of the components in a reactor-like fusion environment. The heat loads on components in a burning plasma experiment will be comparable to those expected in a reactor and as a research issue will require the 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. While some materials testing may be initiated, an evaluation of material lifetimes under expected fusion reactor neutron fluence will not be possible with the low fluence expected in this first burning plasma experiment.

In summary, a burning plasma experiment would be of technological interest particularly with regard to the following issues:

- Breeding blanket development,
- Tritium processing,
- Magnet technology,
- High-heat-flux component development, and
- Remote handling technology.

Readiness to Pursue a Burning Plasma Experiment

Having asserted the scientific and technical interest in a burning plasma experiment, it is prudent to ask if the fusion community is ready to undertake such an experiment. Specifically, the question is whether an experiment designed and constructed with present knowledge can achieve a burning plasma state so that new phenomena present only in such a state can be explored. In assessing readiness, the committee found it useful to define 12 specific scientific and technical criteria—6 in each category—that it judged to be necessary (and sufficient) components of any path to a burning plasma experiment. The committee then assessed the readiness of current science and technology against each criterion. These criteria are discussed in more detail in Chapter 3 and are summarized here.

Following are the six criteria for defining scientific readiness:

1. *Confinement projections.* Reaching the burning plasma regime depends critically on the rate at which energy is lost from the plasma. It is possible to predict accurately the energy-loss rate in existing tokamak experiments through confinement scaling studies; the present level of uncertainty in these projections is acceptable.

2. *Operational boundaries—plasma pressure and current.* Tokamak operation is constrained by limits on the plasma pressure and current. The present operational boundaries and other constraints, including limits on plasma pressure and current, are sufficiently well understood and amenable to control to proceed.
3. *Mitigation of abnormal events.* Burning plasma experiments are designed to handle safely abnormal events such as disruptions, should they occur. While there is confidence that these and other abnormal events can be avoided or mitigated, further research is needed to develop operating regimes that present less stringent heat loads to plasma-facing components.
4. *Maintenance of plasma purity.* Impurities in the plasma—either helium from fusion reactions or from sputtered first-wall materials—can significantly degrade plasma performance. There is confidence that the required plasma purity can be obtained by helium removal and the inhibition of impurity influx from the first wall and divertor.
5. *Characterization techniques.* Techniques are available to adequately characterize and evaluate most of the important parameters in a burning plasma.
6. *Plasma control techniques.* Plasma control techniques are needed that are adequate to produce and evaluate burning plasma physics and to explore steady-state advanced operational regimes. Such techniques have been developed.

Following are the six criteria that define technical readiness:

1. *Fabrication of necessary components.* The required techniques for fabricating components have been successfully demonstrated with prototypes. The components for a burning plasma experiment can be manufactured and assembled, including the required magnetic field coils, the vacuum vessel, divertor, and first-wall components.
2. *Component lifetime in a nuclear environment.* The lifetime of the various parts of a working fusion reactor must be able to minimize the vulnerability to damage from operating in a nuclear environment. There is sufficient assurance that major components can survive in the required nuclear environments.
3. *Lifetime of plasma-facing components.* Prototype designs of plasma-facing components have been tested for normal heat-flux conditions, and it has been demonstrated that the mechanical designs can accommodate the projected disruption forces.
4. *Tritium inventory control.* Safety analyses have found that the proposed

burning plasma devices meet fusion safety standards, and none of the devices requires an evacuation plan beyond the site boundary. The required tritium inventory can be handled safely, but further research is required to develop plasma-facing components that can reduce the tritium inventory.

5. *Remote maintenance.* The required remote maintenance has been demonstrated in operational fusion experiments.
6. *Fueling, heating, and current drive control.* The injection of frozen pellets of deuterium-tritium is a proven method to fuel fusion plasmas. The use of various heating and current drive control systems is well established.

In essence, significant progress has been made in the development of the scientific and technological foundations needed to implement a fusion machine of the scale and nature of ITER. It is clear that ongoing research can be expected to adequately address issues requiring continued attention, but no issues remain that would undermine the fusion community's assertion that it is ready to undertake a burning plasma experiment.

The Next Step?

On the basis of its consideration of the interest in and readiness for a burning plasma experiment, and given the centrality of implementing a burning plasma experiment to the development of fusion energy, the committee affirmed in December 2002 and reaffirms here that the U.S. fusion program should participate in the ITER program. The committee notes that since the issuance of its interim report, the U.S. government has joined the ITER negotiation process as recommended in that report.

Notwithstanding the progress at the ITER negotiations, even on a success-oriented schedule, experiments on ITER could not begin for another 10 years or so. The DOE must consider how to structure its fusion program so that it remains vibrant and positioned to optimize its scientific progress in this time frame and beyond. This effort will be a challenge, as was recognized in the committee's interim report, which included the following recommendation:

> 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 [see Appendix E, p. 157, in this report].

This need was affirmed by DOE Secretary Spencer Abraham in January 2003 in a talk at the Princeton Plasma Physics Laboratory.

> Our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program—at Princeton, at the universities and at our other labs. Critical science needs to be done in the U.S., in parallel with ITER, to strengthen our competitive position in fusion technology.[9]

The preparation for and execution of a burning plasma experiment will be a multidecade activity. The scientific and technological payoff from this experiment will be greatly enhanced by a domestic fusion research program that both supports and complements the ITER program effort, to progress toward the long-term fusion energy goal. These goals can only be achieved through a balancing of the U.S. fusion science program in a dynamic way.

The next section examines the various elements required in a strategically balanced fusion program in some detail. It focuses on the critical science issues to be confronted by the fusion science program, on research activities that could be undertaken over the next several years to prepare for experiments on ITER, on fusion science issues to be addressed in a portfolio of smaller-scale research programs and on the specific goals to be pursued therein, on the need for continuing efforts in theory and simulation, and on considerations of education and workforce development relevant to achieving this overall program.

PROGRAM STRUCTURE

The goal of the U.S. fusion program is to develop the scientific and technological knowledge base for practical fusion energy production. It is thus characterized as a science program with an energy goal. A distinguishing feature of the U.S. fusion program has been the development of understanding at a fundamental level of the physical processes governing observed plasma behavior—a feature that was formalized with the 1996 restructuring of the fusion program. Studies and reports on the program have repeatedly pointed to the science focus of the fusion program as being critical to its success as a source of innovation and discovery for the international fusion energy effort.

Developing any energy source is a long and difficult task. Typically, the time from concept to facility is more than three decades after the basic concept has been proven. Fusion has not reached the stage for building a successful demonstration reactor. A decision to participate in the ITER burning plasma experiment represents a commitment to invest in a large experiment that will advance our scientific

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[9] Remarks of Secretary Abraham are available online at http://www.pppl.gov/common_pics/secretary_remarks.pdf. Accessed May 1, 2003.

and technical understanding in pursuit of the energy goal of the U.S. fusion program. The decision will clearly require the direction of a large amount of resources in the fusion program to support this effort. The ITER project, no matter how successful, is not an end in itself, but only a major step on the road to a larger goal—practical fusion energy. Even on a success-oriented schedule, experiments on ITER will not begin for approximately 10 years. It is natural to ask, therefore, how the DOE fusion program should be designed, recognizing both this timescale and the importance of balancing the pursuit of the critical issues of fusion science needed to establish the basis for fusion energy.

The discussion in the following subsections addresses the breadth of the fusion program necessary to support the development and operation of the ITER facility and to achieve a program in which the critical elements are in balance for reaching the long-range program goals. In addressing these issues, the committee responds to the third element of its charge, which asks for "an independent review and assessment of the plan for the U.S. magnetic fusion burning plasma experimental program . . . [and] recommendations on the program strategy aimed at maximizing the yield of scientific and technical understanding as the foundation for the future development of fusion as an energy source" (see Appendix A). The committee notes, however, that apart from being presented with some short-term budget plans from the Office of Fusion Energy Sciences, progress reports on the state of the ITER negotiations, briefings on the activities and reports of the Fusion Energy Sciences Advisory Committee, and reports on the status of the various elements of the current research program, it was not presented with a coherent and singular strategy for the OFES program. The committee strives to present a foundation for such a strategy in this report, as detailed in Chapter 4.

Today's Balance

The U.S. fusion program is formally defined by its mission:

> [To] advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.[10]

The program has defined three goals to achieve in pursuit of this mission:

1. Advance plasma science in pursuit of national science and technology goals;
2. Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and

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[10] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

3. Pursue fusion energy science and technology as a partner in the international effort.[11]

A strong domestic fusion program necessarily supports all three of these goals, but as with any dynamic and vital research program, the distribution of activities in pursuit of the goals must evolve to reflect current program priorities. The first two elements are often referred to as the core program or base program and include most of the research activities being pursued at present. These efforts provide a foundation for the fusion science program by investigating a range of key fusion science issues. The third element of the program includes participation in an international burning plasma experiment.

In carrying out its analysis of the fusion program, the committee did not find the common characterization of the U.S. fusion program as consisting of a "base program" and a burning plasma program to be particularly useful. The committee found it more important to view the program as a unified, science-driven effort that pursues the fusion energy goal and is composed of a diverse set of complementary efforts.

The U.S. fusion program's pursuit of its three goals has defined the balance of the fusion program. During the past decade the program achieved notable advances in understanding and predicting plasma performance—particularly in the field of plasma theory and experimental work in comparing the results of theoretical and numerical calculations with experiment. Important parts of the evaluation of the scientific and technical basis for an attractive fusion reactor concept can be accomplished in smaller-scale activities. These activities, plus modest support of basic plasma science itself, encompass a wide range of experimental and theoretical investigations. This is referred to as the portfolio approach to fusion science and technology development.

The fusion research portfolio addresses issues of importance to developing the knowledge base for fusion energy. It involves studies of plasma properties across a range of different magnetic configurations to test basic understanding of magnetically confined plasmas, to improve reactor concepts, and to establish the science base that underlies the large-tokamak and burning plasma experimental programs. This portfolio includes programs in theory and computation, advanced diagnostic development, and enabling technology.

The importance of this diversified approach has been affirmed by past outside

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[11] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

reviews. The advances made by the portfolio approach fusion program are documented in detail in the NRC's FUSAC report, which noted the "remarkable strides" in fusion science research. Recognizing the diversified and balanced approach of the current program, the FUSAC report says, "An optimal fusion science program needs two components: experiments in nonburning plasmas to explore the large range of critical science issues which do not require a burning plasma; and experiments in burning plasma. . . ."[12]

While concluding that fusion science "is on a par with the quality in other leading areas of contemporary physical science," the FUSAC study also noted that "a strong case can also be made that a program organized around critical science goals will also maximize progress toward a practical fusion reactor."[13]

The FUSAC report recommended that "increasing our scientific understanding of fusion-relevant plasma should become a central goal of the U.S. fusion energy program on a par with the goal of developing fusion energy technology" as the appropriate approach to fusion energy.[14] This committee reaffirms these findings as guiding principles while embarking on a burning plasma experiment.

It is clear that the commitment to move to a burning plasma experiment will require a substantial reconfiguration of the distribution of activities among the major elements of the domestic U.S. fusion program. In addition to the new activities required to prepare for participation in the ITER program, it will be necessary to substantially refocus many existing activities in support of the burning plasma ITER program. In addition, the balance between science and technology activities is critical. As the committee noted in its interim report: "[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" (see Appendix E, p. 158).

This need for a broad science program has also been recognized by the DOE Office of Science; an occasional paper released by the Office of Science before the decision to reenter the ITER negotiations stated:

> If the U.S. chooses to join ITER, it will be imperative to continue and strengthen the basic elements that have provided the insights leading to the improved ITER design in the first place. The core U.S. strengths in theory and modeling, diagnostics,

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[12] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, pp. 1, 53.

[13] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, pp. 10, 2.

[14] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, p. 3.

> advanced and innovative concepts, and plasma and fusion technologies will be needed to ensure the success of ITER and the pathway to fusion energy.[15]

The balance of the research portfolio of the U.S. fusion program has been successful; it is now clear that a major part of the fusion program will be affected by the U.S. role in ITER. While the negotiations that will define the U.S. commitment are not complete, some general principles are clear. Accepting the need for a major investment in ITER, it is essential to consider the issues that will affect the balance of the portfolio of the U.S. fusion program following this significant change. The following discussion is framed in the context of the next few years. It provides only general guidance for the rest of the decade, because increased understanding of phenomena such as turbulence, transport, and magnetic reconnection is likely to change in very significant ways the course of ITER experiments.

Primary Issues of Fusion Science Research

The pursuit of the three fusion program goals, as detailed above, supports the development of the knowledge base for an attractive energy source and has effectively defined a balanced fusion program. The third element of the program encompasses participation in international burning plasma experiments, an element that was considerably deemphasized upon the withdrawal of the United States in 1998 from the original ITER program. The first two elements include most current research activities on non-burning-plasma issues—such as plasma stability, nonlinear turbulence, self-organizing systems, magnetic field symmetry, and plasma sustainability at high pressure—by studying plasma behavior across a portfolio of advanced tokamak and non-tokamak confinement considerations. The activities range from relatively large national experiments on advanced tokamaks and the related spherical torus configuration to small university-scale experiments studying a range of non-tokamak confinement concepts. The larger facilities are well diagnosed and pursue simultaneous studies of a wide range of fusion science topics in near-reactor conditions, while the smaller devices are typically focused on specific topics, which can be addressed in detail with less overall capability and diagnostic coverage. This program rests on a foundation of research in theory and simulation, advanced diagnostic development, and enabling technology developments.

The U.S. fusion program is focused on innovation and optimization, based on

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[15] "Fusion Energy—Bringing a Star to Earth," available online at http://www.sc.doe.gov/Sub/Occasional_Papers/6-Occ-Bringing-a-Star-to-Earth.PDF. Accessed May 1, 2003.

developing predictive understanding of the underlying physics (see Chapter 4 for a more in-depth discussion of the program). Accomplishing the program goals has required and continues to require the investigation of the following primary and compelling issues:

- *Plasma turbulence and turbulent transport.* A key to high fusion performance in burning plasmas is the suppression of turbulence and the transport of pressure and particles that it generates. Over the past two decades, a number of methods to suppress ion turbulence have been discovered, including stabilization by sheared flows. These experiments, together with continued progress in theory and simulation, will lead to improved predictive understanding of turbulence suppression.
- *Stability limits to plasma pressure.* Increasing the plasma pressure that can be confined stably is key to developing more attractive fusion energy. Consequently, all of the research on magnetic configurations seeks to increase the maximum stable pressure limit.
- *Stochastic magnetic fields and self-organized systems.* For configurations in which plasma currents dominantly produce the magnetic field, or those in which the plasma is unstable owing to tearing (or reconnection) instabilities, the magnetic field can become stochastic or turbulent, leading to a loss of particles and energy. A number of experimental efforts to investigate magnetic reconnection—along with complementary theory and simulation programs—have clarified, although not yet completely illuminated, the physical mechanisms involved.
- *Plasma confinement with different types of magnetic field symmetry.* In tokamaks and most of the other magnetic configurations, the magnetic field does not vary in the toroidal direction and thus is toroidally symmetric. Theoretical studies have demonstrated that good particle orbit confinement can be achieved in three-dimensional stellarator magnetic configurations by making the magnitude of the magnetic field strength be constant along a specified direction in a suitable flux coordinate system. The resulting quasi-symmetric (helical) configurations have already begun operation and observed signatures of confinement improvement.
- *Control of sustained high-pressure plasmas.* Steady-state operation greatly increases the economic appeal of fusion systems. Efficiently sustaining and controlling high-pressure plasmas therefore constitute a critical issue. While theoretically optimized solutions have been found, experiments have not yet observed steady-state-compatible high-pressure plasmas consistent with low amounts of external current drive. These investigations are crucial for establishing the benefits of the various fusion configurations.

- *Energetic particles in plasmas.* A number of experiments have investigated how energetic particles—often beams of particles—excite waves and instabilities in plasmas. The theory of nonlinear wave-particle interaction has advanced considerably in the past 20 years and has been extensively validated against experiments. Different magnetic configurations can be more or less stable to these waves, offering opportunities for improvement.
- *Plasma behavior when self-sustained by fusion (burning).* In a burning plasma, the dominant heat source arises from the fusion-produced fast alpha particles. This is fundamentally a nonlinear process, which will combine with the turbulent transport processes to modify the plasma equilibrium and stability properties. In addition, the fast alpha particles can directly generate fluctuations in the plasma and thereby influence the confinement of the alpha particles and possibly the background thermal plasma itself. The net result is a highly nonlinear plasma regime with strong elements of self-organization. Plasma regimes with the relevant population of fast alpha particles in a reactor-relevant size of experiment are accessible only in the proposed burning plasma experiments.

Having considered the primary and compelling issues facing the U.S. fusion program as it pursues the program goals, it is also appropriate to consider what the opportunities are for the fusion program as it prepares to incorporate a burning plasma program. In particular, the committee considered the following questions in its analysis: What are the needs of the burning plasma program on ITER? What are the goals of the concept-optimization programs? What role is there for novel concepts? What is the importance of developing fusion technologies? These issues are addressed below, followed by a discussion about the workforce and education issues that face the fusion program and the fusion community.

Research Opportunities and Science and Technology Goals for the Next Decade: Direct Support of the Burning Plasma Program on ITER

The preparation for and execution of a burning plasma experiment will be a multidecade activity. While there is every confidence that ITER will be a successful scientific endeavor, a number of scientific and technological issues must be addressed to prepare for and make the best use of a burning plasma experiment.

ITER is a tokamak confinement device, and a wide range of issues can be addressed in the domestic and world tokamak programs to prepare for and improve concepts for operation of the ITER experiments. From an examination of recent studies, the NRC FUSAC review, other community reviews, and presentations to this committee, the committee has identified key areas in which ongoing

U.S. research and development can make significant contributions in order to gain the maximum benefit from participation in a burning plasma experiment. The committee believes that these activities will be a significant part of the domestic program—in coordination with the international partners—to support and prepare for the operation of a burning plasma experiment. These activities define a substantial part of the role that tokamaks can play—with associated theory, diagnostic, and technology development—as ITER is constructed and operates. The issues to be addressed in support of the burning plasma program are discussed in detail in Chapters 2 and 3. A short summary is given here:

- *Theoretical understanding and modeling.* This area includes the development of improved models of the edge plasma and pedestal, density limits, core confinement, and MHD instabilities.
- *"Pedestal" profiles in high-confinement plasmas.* Work is needed to develop a first-principles theoretical understanding of this phenomenon in order to allow fully predictive transport models from the edge to the hot core region.
- *Turbulent transport.* Understanding the transport in high-confinement mode (H-mode) discharges could lead to increases in energy gain and/or to operation at reduced current and magnetic field.
- *Edge-localized modes (ELMs).* Understanding of these modes is needed in order to mitigate their effects on plasma-facing components, especially in the burning plasma regime.
- *Stabilizing neoclassical tearing modes.* Controlling these high-pressure instabilities will expand the operation space of burning plasmas.
- *Advanced tokamak operating regimes.* Developing the physics basis for long pulses before the initiation of ITER experiments would enable more effective use of ITER.
- *The density limit and high-density operation.* The energy gain and purity of burning plasmas are favorably affected by increasing the plasma density.
- *Tritium retention in plasma-facing components.* Additional research on materials and tritium transport, together with the development of alternative plasma-facing components, can be used to ameliorate this issue, thereby decreasing the potential for ITER downtime.
- *Disruption avoidance and mitigation.* The extension of new gas-injection suppression techniques to ITER scale will reduce the effects of disruptive plasma terminations.
- *Divertor development.* Divertor solutions at lower plasma densities with improved heat-flux capabilities are needed for exploring alpha physics and steady-state operating scenarios.
- *Plasma-facing components.* The improvement of these components is a key

issue for ITER research and development. New designs must be further developed for fabrication with large-area manufacturing techniques.

- *Diagnostic development.* The deployment of complex measurement techniques in a hostile radiation environment requires their careful integration into the facility design; a burning plasma requires new measurement capabilities for analysis and control.
- *Radio-frequency heating and current drive technology.* Robust antenna designs and sources are needed to provide heating and current drive capabilities in a burning plasma.
- *Tritium breeding blankets.* Research on tritium breeding using ITER is necessary to secure sufficient fusion fuel supplies for follow-on fusion devices.

Research Opportunities and Science and Technology Goals for the Next Decade: Concept-Optimization Research

In addition to the goals of the burning plasma program on ITER, the committee considered roles for the four largest concept-optimization research programs. Its specific scientific goals for each of these programs are summarized below:

- *Develop an understanding of paths to advanced tokamak regimes.* The advanced tokamak (AT) is a variation of the tokamak confinement configuration. It uses active profile optimization and MHD mode stabilization to provide, in principle, steady-state operation at high pressure and enhanced confinement, with the self-generated bootstrap current sustaining almost the entire plasma current. The AT employs active control of accessible plasma profiles (e.g., heating, density, pressure, and so on) to provide this enhanced performance. The integration of these varied tools and characteristics into a self-consistent scenario is a major focus of research. AT experiments in smaller facilities with a range of control tools and plasma-shape capabilities will complement and guide the AT studies in the burning plasma program and in ITER itself.
- *Test the effects of extreme toroidicity in the spherical torus.* The spherical torus (ST) is attained when the toroidal aspect ratio of a tokamak is reduced toward its absolute lower limit (i.e., the hole in the center of the torus is reduced to a small fraction of the plasma radius). The study of ST plasmas is of interest because it challenges tokamak-based physics understanding at the limits of toroidicity and shaping and provides access to plasmas of very high relative pressure and high fraction of self-generated currents. The ST may also provide a reduced-cost path to the development of fusion energy.

- *Investigate sustainment and enhanced confinement in the reversed-field pinch.* The reversed-field pinch (RFP) is a toroidally symmetric configuration in which the magnetic fields are generated mainly by internal plasma currents. These currents result in the toroidal field's changing direction near the plasma edge region (hence the name). The RFP provides a laboratory test of nonlinear plasma relaxation properties found in nature and the laboratory. An RFP reactor may present attractive properties, arising from low magnetic fields and high plasma pressure (relative to the magnetic pressure). The RFP is at a level of development considerably less mature than that of the tokamak.
- *Explore the potential for passive stability and steady-state operation in three-dimensional stellarators with underlying magnetic symmetry.* The stellarator is a toroidal configuration in which the magnetic fields needed for plasma confinement and stability are generated by twisting the shape of external coil sets to produce closed magnetic-flux surfaces. The stellarator does not require externally driven plasma current—allowing very efficient steady-state operation and, potentially, greatly reduced susceptibility to current-driven instabilities. The near-term focus is to test the benefits predicted with magnetic symmetry using three-dimensional shaping, to examine more compact stellarator configurations, and to explore plasma shapes that are predicted to be able to operate at high normalized plasma pressures.
- *Explore novel and emerging fusion science and technology concepts.* Small-scale experiments can address some unique fusion research issues, which may be relevant to near-term applications of fusion science and technology or allow the study of speculative, emerging concepts for advanced fusion systems. These experiments, and their associated theory efforts, address basic issues of formation, equilibrium, and stability. They promise potentially more compact fusion scenarios. The spheromak and field reversed configuration (FRC) are in this class—both are somewhat similar to if less mature than the reversed-field pinch.
- *Develop fusion technologies to enable innovative fusion science experiments and provide attractive long-term reactor concepts.* The pursuit of a burning plasma experiment requires the development of new technologies to produce and study burning plasmas in ITER. In addition to developing those technologies related to the burning plasma program, the domestic fusion program, in collaboration with international partners, must advance the knowledge base for fusion energy by addressing issues in three main areas: plasma technologies in support of advanced fusion science experiments, plasma chamber technologies, and fusion materials. Regardless of the de-

> gree of commitment to developing a fusion reactor in any specific time frame, research activity in these areas supports the long-range goal of developing attractive fusion concepts.

The committee agrees that, generally, the aggregate level of activity discussed above is needed both to support the move to a burning plasma program and to maintain a vibrant, productive domestic research program that is making progress toward the long-range goal of establishing the knowledge base for fusion energy. The committee notes that the range of activities presented here is strictly representative and is not meant to be proscriptive. The choice of which opportunities to pursue—including consideration of the U.S. fusion program goals and international fusion activities—must be determined by the usual federal government process, advised by the fusion community, as described later in this report.

Theory, Simulation, and Computation

Transferring knowledge of burning plasmas to other elements of the fusion program will require a detailed theoretical understanding of the fundamental physical processes involved. If the U.S. magnetic fusion program is to take full advantage of ITER, it will be necessary to develop a first-principles understanding of the phenomena that determine ITER's performance. This will require the development of improved models of the edge plasma, transport barriers, density limits, core confinement, and MHD instabilities. Success in this endeavor will require a continued program of experiment, theory, and modeling, including a strong experimental program on ITER itself.

It has long been recognized that the complexity of the burning plasma problem precludes the use of purely analytical methods to yield the desired fidelity. Computer models of parts of the entire system were developed instead. This approach has led to a new level of understanding and has served the fusion program well. However, significant near-term challenges remain in the areas of plasma edge physics, turbulence on transport timescales, global macroscopic stability, and their extensions to a burning plasma regime. The problem of modeling systems with widely disparate time and space scales has been dealt with so far by the use of reduced descriptions, but at some stage of investigation the coupling between the reduced regimes becomes important and presents formidable challenges. An example of the complexity involved is what is called plasma edge physics. The plasma edge region, at the outer boundary of the plasma, is one of rapidly varying density, and it strongly influences stability.

Going forward, a program in theory and simulation must rely on a marriage of advances in information technology, plasma science, applied mathematics, and future developments in software. The computation and simulation part of the fusion program will need attention and possible expansion for the ITER program.

The Role of the Universities: Research, Education, and the Fusion Workforce

The role of the universities in the fusion program is manyfold. The universities train the students who will fulfill the future workforce needs of the field. The universities serve as centers for research with long-term perspectives, in both experiment and theory. University research generates and nurtures new scientific and technological ideas, and it leverages new knowledge from other fields of science. University theoretical efforts make connections with concepts from other fields, such as fluid dynamics, plasma astrophysics, and materials-related plasma science. Local experimental facilities are testbeds for new ideas, and they give students immediate, hands-on experience in plasma and fusion science. University user groups play important roles in experiments at larger facilities. As fusion devices become larger and experiments are further coordinated on the worldwide stage, this trend—which has long been standard in astronomy, high-energy physics, and nuclear physics—can be expected to become even more important.

The ramp-up to a burning plasma experiment poses special challenges in meeting workforce needs, particularly in light of the workforce demographics in fusion and plasma science and engineering. Extending beyond the needs of the burning plasma experiment is a pressing need to replace aging personnel in fusion and plasma sciences in the universities and the national laboratories.[16] In comparison with other fields, university fusion and plasma sciences faculty members are older than their counterparts, with comparatively fewer new hires in the field.[17] The situation is similarly critical at the nation's three largest fusion science laboratories, where there is a significant bulge in the scientific workforce in the 50- to 60-year-old age group.[18] Meeting these personnel needs is a key function of the university fusion programs. As expressed in the committee's interim report, "New people are required if the nation is to expand its [fusion] efforts and make the program endure. The necessity of attracting graduate students and postdocs into

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[16] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, p. 13.

[17] E. Scime, K. Gentle, and A. Hassam, *Report on the Age Distribution of Fusion Science Faculty and Fusion Science PhD Production in the United States*, College Park, Md.: University Fusion Association, July 2003.

[18] Committee co-chair Raymond Fonck, private communications with personnel at the fusion science laboratories mentioned, May 2003.

the program requires that it have a strong university-based component" (see Appendix E, p. 158). If support is not available for faculty and graduate students in plasma and fusion science, scientists and engineers will move to other areas of concentration.

Recent assessments of university plasma and fusion programs reveal another challenge to training new fusion personnel. The 1995 NRC plasma science study[19] and 2001 NRC FUSAC report found the fusion community to be relatively isolated from other fields of science and engineering. This isolation has many detrimental effects, including reduced appreciation for fusion science, decreased support for faculty appointments in fusion science, and reduced access to the broad population of science and engineering students. The University Fusion Association's recent survey of university plasma and fusion science programs shows a decline of fusion science positions in the most highly ranked academic institutions in the United States.[20] These programs tend to be the largest, most visible university fusion programs. The University Fusion Association's survey of 10 of these large institutions indicates that 15 out of 66 faculty will reach retirement age in the next 5 years, while their institutional plans call for hiring at the very most 9 faculty members over the next 5 years. The conclusion is that the presence of fusion science research in the top 25 physics and engineering programs is *declining* just as the program is attempting to move toward ITER and the study of burning plasmas. This decline also raises the danger of further isolation of the fusion community from the larger scientific community.

New personnel with special technical training—beyond the conventional science and engineering degrees—will be needed to design and build the burning plasma experiment. The current pool of technical personnel is inadequate to fill this need. This shortage is due in part to the fact that the United States has built only one major fusion device in 20 years. With the redirection of the fusion program to a science program in 1996, the number of U.S. fusion technology personnel decreased by 50 percent, and support for specialized technology research facilities was reduced. Full participation in the burning plasma experiment will require that specific attention be paid to revitalizing the fusion technology workforce.

The potential payoff of a broad and freely structured program of long-term

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[19] National Research Council, *Plasma Science: From Fundamental Research to Technological Applications*, Washington, D.C.: National Academy Press, 1995.

[20] E. Scime, K. Gentle, and A. Hassam, *Report on the Age Distribution of Fusion Science Faculty and Fusion Science PhD Production in the United States*, College Park, Md.: University Fusion Association, July 2003.

university research requires that it continue to be an important part of the U.S. fusion program. There will continue to be a need for small-scale plasma and fusion programs with single or small groups of principal investigators. Maintaining a concentration of funding at only a few major facilities, pushing small-scale projects aside, makes the withering of these programs a real possibility.[21] Similarly, there is a danger that a concentration of theory funding for only tokamak and burning plasma problems will lead to the evaporation of support for other important areas. There is much to be gained by maintaining innovative smaller programs in terms of both generating new ideas and attracting new talent.

The federal fusion program must be the steward of plasma science in order to maintain the flow of new ideas and new talent into the field of fusion science. Although the fusion program has made important contributions to basic physics knowledge in areas such as fluids and nonlinear dynamics,[22] plasma research does not stand out as a priority in long-range planning among physics and engineering departments. Beyond basic plasma research, important university efforts include smaller-scale tokamak and alternate-concept experiments, as well as participation in the larger national programs. While the specific projects to be pursued will change as the fusion program evolves, the important role of university research in the U.S. fusion program will continue throughout the era of the burning plasma experiment and beyond.

Prior to the recent U.S. decision to rejoin the ITER negotiations, the Office of Fusion Energy Sciences took several important actions that help to increase the talent pool and ensure the vitality of the basic plasma research efforts in the universities. OFES established a Principal Young Investigator program in plasma science and several small-scale experimental programs via the Innovative Confinement Concepts activity. It also took a leading role in creating the DOE/National Science Foundation program in basic plasma physics. The level of support for these programs, and other measures to revitalize the fusion workforce, should be responsive to the research and personnel needs in the era of the burning plasma experiment.

The material presented here indicates that many plasma and fusion science faculty and fusion laboratory personnel are approaching retirement and that there may be a serious shortage of professionals in the future as ITER develops and the

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[21] According to the FY 1985 and FY 2000 budget tables for OFES: in 1985, funding for the nation's fusion laboratories (including the Massachusetts Institute of Technology) accounted for 93 percent of the OFES budget; in 2000, it accounted for 83 percent of the OFES budget.

[22] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program,* p. 72.

program expands. However, as OFES funding improves, this outlook may become more positive. It is appropriate for OFES to initiate a review of the demographics with respect to this problem, utilizing historical time lags between funding, staffing, and graduate student enrollment. Expanding the percentage of funds going to university programs could attract more plasma and fusion science students and postdoctoral researchers and should increase the visibility of fusion science in the universities. OFES should examine the benefits of such a strategy as well as the negative effects on the non-university programs and staffing. OFES also should address how the large facilities can become more effective user facilities to integrate a larger university contribution, similar to the modes of other facilities supported by the DOE Office of Science.

The ITER Negotiations and Program Contingency

The pace of the ITER program will be decided by the participants through the negotiating process. The U.S. component will be settled as the negotiations proceed and as procurement packages are assigned and construction preparations commence. Those negotiations will determine the U.S. financial contribution to ITER construction and will determine the role for and demands on the U.S. fusion program as an ITER partner.

In its interim report, the committee listed a minimal level of participation in the ITER program to which the U.S. fusion program should commit in order to gain sufficient benefit from this opportunity to study burning plasmas. It said, "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" (see Appendix E, p. 157).[23] The committee reaffirms this conclusion. Involvement in high-technology components is important in order to challenge and sustain the domestic program's vitality; without this type of activity, the U.S. readiness for fusion power will not be sufficiently leveraged off ITER.

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[23] The committee notes that the text in the interim report has a comma between the words "facility" and "consistent" in this quotation. Since publication of that report, the committee has become aware of the potential for the original formulation being interpreted in a manner inconsistent with the committee's intent. Therefore, as shown in the Summary and in the list of recommendations later in this chapter, the committee has removed the comma. The removal of the comma reasserts the committee's intended meaning, namely, that the U.S. role in producing the high-technology components of the facility be consistent with the size of the U.S. contribution.

Recognizing the importance of the negotiating process to the future of the U.S. program, the committee also made some recommendations in its interim report to the Department of Energy. Specifically, the committee recommended 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. . . .
> 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 [see Appendix E, pp. 160-161].

The committee was pleased to learn that a preliminary and successful review of the construction costs for ITER was conducted and considers this an important first step in understanding the potential costs of the ITER program for the United States. Furthermore, the committee understands that the DOE is carrying out an analysis of the various work packages that will be of primary interest to the U.S. fusion program and that it has engaged the fusion community in this effort through the establishment of a Burning Plasma Program Advisory Committee and the holding of an ITER forum for community input. The negotiating process remains critical to defining the future of the U.S. fusion program. With this in mind, the committee reaffirms the DOE actions recommended in its interim report and quoted above.

Notwithstanding the goodwill of all of the negotiating parties and the significant progress made to date, it is important to recognize that the ITER negotiations could be unsuccessful, and reasonable contingency planning for that eventuality is prudent until a decision on ITER is reached. In the case of failure to proceed with ITER, the world community would naturally reassess and look for an alternative approach to a burning plasma experiment that most likely would become an international collaboration. All potential participants would want a role in the choice of parameters and the final design of such an experiment. The FIRE concept represents one possible contingency that could be considered in this context. Depending on the circumstances, the partners would need to reassess the optimal path for the development of a burning plasma experiment. Because a burning plasma experiment is a key step on the necessary scientific critical path toward fusion energy, any delays in realizing such an experiment—such as failure in the ITER negotiations—will necessarily delay the domestic program's ability to address and understand fusion science questions that must be answered before practical fusion power can be developed.

STRIKING THE BALANCE

Summary of Findings and Discussion

The U.S. fusion program, after many years of research, is poised to take a major step toward its energy goal. It is clear that a burning plasma experiment is a necessary step on the road to fusion energy and of scientific and technical interest to the U.S. fusion program and beyond.

It can be expected that a burning plasma experiment will make critical contributions to understanding fusion science and fusion technology issues such as the following: behavior in a self-sustained burning plasma burn, fusion-plasma turbulence and turbulent transport, stability limits to plasma pressure, control of a sustained burning plasma, power and particle exhaust challenges, breeding blanket development, tritium processing, magnet technology, high-heat-flux component development, and remote handling technology. In addition, a burning plasma experiment may make useful contributions to the basic understanding of plasmas on issues such as magnetic field line reconnection, plasma turbulence, abrupt plasma behavior, and energetic particles in plasmas.

Recent studies inside and outside the fusion community agree that the U.S. fusion effort is scientifically and technically ready to undertake such an experiment and that ongoing research can be expected to adequately address issues requiring continued attention. The critical issues on which confidence is now high are these: confinement projections; operational boundaries—plasma pressure and current; the mitigation of abnormal events; the maintenance of plasma purity; characterization techniques; plasma control techniques; fabrication of necessary components; component lifetime in a nuclear environment; the lifetime of plasma-facing components; tritium inventory control; remote maintenance; and fueling, heating, and current drive control.

Having considered the options for a burning plasma experiment, members of the fusion community arrived at a consensus that the United States should seek to join the ITER program. Preparations for the ITER project are well advanced, and the U.S. government began participating in the ITER negotiations in January 2003.

The pursuit of a burning plasma experiment is a large undertaking that will necessarily require a major shift in the distribution of activities in the U.S. fusion program, not only now but as the ITER program evolves and develops. A large portion of the U.S. fusion program will focus directly on the burning plasma experiment as a centerpiece of the program, including activities needed to support the development and operation of the ITER facility.

Considering the discussions earlier in this chapter and in the remainder of the report, the committee has found that the broad range of fusion science studied on a burning plasma experiment and by non-burning-plasma smaller-scale research efforts are complementary and tightly intertwined. Pursuing one at the expense of the other seriously weakens the entire enterprise.

The list of compelling basic plasma physics questions that will define the U.S. commitment to ITER is not complete. However, once the decision is made, fulfilling the international commitment to help construct the ITER facility and participate in the ITER program will necessarily become the highest priority in the program. Given the magnitude of this step and the need to support it in full, it is clear that a new balance will need to be struck among the elements of the U.S. fusion program. This rebalancing is required especially because finite funding resources cannot be expected to support all possible interests of the community. The restructured program may be considered an evolutionary change from the present structure, but nonetheless it will require changes across the whole fusion program.

This evolution in the program must be accompanied by the recognition of the strong interconnection among all elements of the expanded program. The often-cited distinction between an existing base program and a separate burning plasma program is no longer relevant or useful, and indeed it impedes the development of a unified rationale for the required broad-based program and undermines the support for the constituent parts of the program. As the burning plasma program elements move forward, they will be necessarily integral parts of an overall balanced program. Decisions on programmatic priority should be guided by the goal of optimizing the scientific output of the entire program, with due recognition for other program needs—for example, workforce development.

Compelling basic plasma physics questions remain to be addressed. In addition, and because of the need to continually maintain a plasma-physics-literate workforce, another element of the restructured program will need to be the continued support for stewardship of the field of basic plasma science. Although this need commands a relatively small fraction of actual resources in the U.S. fusion program, it is a critical component of any U.S. fusion program structure. Finally, the program requires a fusion technology component whose scale is commensurate with the level of commitment and the timing required to achieve the fusion energy goal. However, the technology programs at this point will be those focused on technologies that will enable a successful burning plasma experiment, that is, primarily those technologies important for the development of ITER.

The endorsement of the merits of these varied activities in the program by this committee does not mean that every activity can or even should be supported unconditionally. Under any funding scenario that can be reasonably expected, decisions will need to be made about the relative priority of activities to pursue at any given time. Since the fusion program is a science-based program, these priorities need to be based on a discussion of scientific opportunities and goals. The need for setting priorities is discussed in the subsection below, "Setting Priorities to Strike the Balance."

Implications for the Fusion Community

The guiding principle in preparing for U.S. participation in the ITER program is the need to position the U.S. fusion community to optimize the scientific output of its activities in the burning plasma program. This need has been addressed so far in this report by considering a technical level of participation. It is important for participation in the ITER program, and indeed for the entire U.S. fusion program, that the community consider changes in the way that it operates in order to position itself to provide the intellectual leadership of chosen areas of research and to optimize the return on its investment.

The choice of major research thrusts will be determined by the government with significant input from the fusion community; examples might include elements of advanced tokamak development, stabilization of large-scale MHD instabilities, turbulence and transport studies, and so on. This approach requires the organization of the community around campaigns that are based more on scientific issues than on the operation of individual facilities. Such an approach appears to be working well in the European program for the operation of JET.

A transition to collaborative research based on scientific issues is a model to be considered for the entire U.S. program as it moves forward. Organizing the research efforts on the larger domestic facilities—the advanced tokamaks, spherical torus, stellarator, and reversed-field pinch—in a similar manner will support the transformation of the community to more of a user-group model and will more effectively engage the research community in these efforts.

While the nature of fusion science research has its unique features, the community can profitably learn how to coordinate dispersed national and international collaborations from other areas of "big science," such as the high-energy and astrophysics communities. This will both optimize the large investments needed in the domestic program and provide practical experience for participation in the ITER program.

This transformation of the culture of the program will take time and could even be somewhat demographically driven to minimize disruption. However, it is important to start now in making this transformation so that a vibrant domestic research program with a sufficient workforce for fusion-grade facilities is available, and so that the community is intellectually and sociologically positioned to optimize its participation in the ITER program as well as optimally exploiting its domestic faculties.

Budget Implications

As stated in its interim report, the committee recognizes that pursuing participation in ITER with a balanced program "will eventually require a substantial augmentation in fusion program funding in addition to the direct financial commitment to ITER construction" (see Appendix E, p. 157). However, the incremental funding requirements for the recommended program likely will be relatively small in the initial years, which should minimize the competition for funds within the overall federal research budgets.

Since the negotiations on U.S. participation in ITER are just starting, it is not possible to estimate the exact level of funding needed to pursue a viable research program at ITER.

The committee is concerned about the pressures on the U.S. fusion program as the United States moves into the ITER program if there is no increase in funding for the OFES. It is important to recognize that the costs of fabricating ITER and its components during the construction phase do not provide any significant support for the science and technology workforce in the fusion research community. While much of the research and development to support ITER has been done, a modest increase in technology and engineering support must be made available to support the negotiations and address some remaining issues, as well as to help mitigate technical risks during ITER construction. Most of the funds for ITER construction will go to those companies that will actually manufacture the components.

A flat budget for the OFES will degrade the scientific research support in the fusion program, inevitably leading to decay in facilities and a decline in research opportunities. A constriction of the U.S. fusion program to pay for ITER participation will disproportionately weaken the presence of the fusion program in academia; it will also further erode connections to the wider scientific and engineering community while reducing the career prospects for critically needed new young talent. In a similar vein, reduced effort on all of the large national facilities will reduce the critical activities needed by the U.S. community both to allow significant contributions to the planning of ITER research and to pursue configuration optimization. Such a reduced effort, in turn, will increase the risk that the United States will play a following instead of a leading role in the ITER scientific program. Similar considerations are clearly relevant for theory and simulation and for technology. Overall, this approach weakens the very structures needed to optimize the benefits of the investment in the ITER program. A clear example of this kind of weakening has already been set in motion, as much of the fusion technology program that was focused on developments beyond ITER was eliminated in the FY 2004 budget. Overall, this is precisely the wrong approach and should not be taken.

A funding trajectory that avoids these risks would provide the support to capture the long-term benefits of joining the international ITER collaboration while retaining a strong scientific focus on the long-range goal of the U.S. fusion program. This approach would support the fusion research field as a vibrant and exciting field with opportunities for attracting outstanding young talent into the field, as well as increasing the connections of fusion research to the other fields of science and engineering in academia. As important, such an approach will position the U.S. contingent in the ITER project to be leaders in significant fractions of the overall program.

Estimates of the funding level needed to maximize the benefit from participation in ITER within the context of a balanced fusion energy program can vary significantly, depending on the areas of U.S. contributions to the ITER program that will be determined in the negotiations. Additional funding for burning-plasma-related support activities and augmentation of the core science program were estimated by FESAC and the DOE Office of Science in briefings to the committee at $50 million to $100 million per year, without elaboration.

It is clear that, at a minimum, in order to capture the benefits of a burning plasma experiment, augmenting the U.S. fusion program to cover all of the U.S. ITER construction and operating costs would be required.

In addition, for the committee's recommendations to be implemented, several elements of the resulting program will require increased investment:

1. The U.S. share of ITER fabrication and experimental operation,
2. Investigations on present facilities and diagnostic development that directly support preparation for ITER,
3. Support for university programs and for theory and simulation,
4. An increased technology program, and
5. Increased utilization of programmatically relevant, larger national experimental facilities.

These areas of increased investment need to be balanced against currently ongoing and planned activities. The balancing process also could be guided by a multiyear budget-planning path that projects funding growth, within the broad ranges described above.

The committee has concluded that a prioritization process is needed to decide on the appropriate programmatic balance, given the science opportunities identified and the budgetary situation of the time.

Setting Priorities to Strike the Balance

The elements and thrusts of the U.S. fusion program are complementary and intertwined. However, a constrained federal budget environment is likely to continue during the period of ITER implementation, and arguably this will be the greatest influence on the building of a balanced U.S. fusion program that includes participation in the ITER program. Notwithstanding the success of the current portfolio approach to the U.S. fusion program, the budget stress facing the program is real and ongoing. The investment in ITER will be significant and must be accounted for in pursuit of a balanced U.S. fusion program. The OFES and the fusion community will have to make serious judgments with respect to priorities in determining the activities at all stages of the fusion program.

The endorsement of the merits of the program activities outlined in this report does not mean that every activity can or even should be supported unconditionally. Any funding scenario that can be reasonably expected will necessitate deciding the relative priority of activities to pursue at any given time. As the U.S. fusion program rebalances its priorities in light of commencing burning plasma studies, some lean years may be expected. The choice of which opportunities to pursue—and which program activities not to pursue—must be determined by the usual federal government process, advised by the fusion community and cognizant of international fusion efforts.

Active planning has been undertaken by the U.S. fusion community in recent years. However, the addition of so major a new element as the ITER program requires that, in order to ensure the continued success and leadership of the U.S. fusion program, the content, scope, and level of U.S. activity in fusion should be defined through a prioritized balancing of the program. A rigorous evaluation of the program priorities should be undertaken by the OFES, with broad-based input from the fusion community. This priority-setting process should be guided by the stated objective of maintaining a balanced program, as discussed in this report.

The committee concludes that in order to develop a balanced program that will maximize the yield from participation in a burning plasma project, the prioritization process should be organized with the following program objectives in mind:

- Advance plasma science in pursuit of national science and technology goals;

- Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and
- Pursue fusion energy science and technology as a partner in the international effort.

Through the prioritization process, the fusion community should identify and prioritize the critical scientific and technology questions to address in concentrated, extended campaigns, similar to the planning done for other areas of science such as for high-energy physics. A prioritized listing of those campaigns, with a clear and developed rationale for their importance, would be very helpful in generating support for their pursuit, while also developing clear decision-making processes in the fusion research community. Further discussion of possible models for this process and the types of questions that participants in the process might ask in the making of real priorities are presented in Chapter 4.

This prioritization process represents a reasonable form of risk management in the overall planning of a fusion program that stretches over several decades. It requires the identification of those issues that may be most uncertain and/or will have the greatest impact on decisions of future directions and investments. Addressing and resolving such issues will help maintain program focus and will continually improve the case for viable fusion energy.

Any future development of larger domestic experiments and any definition of future program needs will be driven by the parallel evolution of related activities in the international community. The international coordination of large science efforts can avoid duplication and exploit opportunities to perform leading-edge research on the best facilities in a cost-effective manner. It is thus important that consideration be given to coordinating with the global fusion program the broad range of fusion activities, including non-ITER-related programs, as appropriate.

Finally, the committee is convinced that the implementation of a process of program prioritization will go a long way toward ensuring the best balance of the U.S. fusion program and its continued vitality and leadership.

CONCLUSIONS AND RECOMMENDATIONS—ELEMENTS OF A STRATEGICALLY BALANCED FUSION PROGRAM

Conclusions

Conclusion: Participation in a burning plasma experiment is a critical missing element in the U.S. fusion science program.

The committee concludes that the scientific and technological case for adding a burning plasma experiment to the U.S. fusion program is clear. During the past decade, the portfolio of activities within the U.S. fusion program has achieved notable advances in understanding and predicting fusion-plasma performance. Because of the progress made in fusion science and fusion technology, there is now high confidence in the readiness to proceed with the burning plasma step. It is also clear that progress toward the fusion energy goal requires the program to take this step and that the tokamak is the only fusion configuration ready for implementing such an experiment.

> **Conclusion:** Participation in the International Thermonuclear Experimental Reactor (ITER) program provides the best opportunity for the United States to engage in a burning plasma experiment.

Of the choices proposed for U.S. participation in a burning plasma experiment, ITER, with the United States as a significant partner, is the best choice for a burning plasma experiment. It is the most mature design and, in the committee's view, is both sound and carefully planned. It is sufficiently conservative in design to provide great confidence in achieving burning plasma conditions, while flexible enough to test critical advanced tokamak operating regimes in steady-state burning plasma conditions. It also allows tests of several fusion-relevant technology issues. Participation in the ITER program also leverages very effectively the U.S. investment in a burning plasma experiment. However, participation in ITER is a major modification to the U.S. fusion program, and the U.S. fusion effort requires a strategically balanced program in the context of meaningful participation in ITER to optimize the scientific output of this investment.

> **Conclusion:** The fusion effort requires a strategically balanced program in the context of U.S. participation in ITER in order to optimize the scientific output of this effort and to maintain the readiness to exploit the outcomes of the fusion program as a whole.

> **Conclusion:** In developing the U.S. fusion science program with participation in ITER, it will be important to maintain the diversified character of the U.S. program. In particular, the vitality of the U.S. program requires a diverse range of activities in the domestic and the international suite of current and planned tokamak and non-tokamak facilities.

When considering the balance of the U.S. fusion program, it is essential to analyze the program as a unified, science-driven effort in pursuit of the fusion energy goal and composed of complementary and diverse efforts. All three elements of the U.S. fusion program, outlined above in the section entitled "Striking the Balance," are essential. The committee concludes that the strength of the U.S. program is in its science-based foundation. It will, therefore, be essential to maintain a strong program in fusion and plasma science as a companion to a major facility program such as ITER.

The outcomes of the negotiations to join ITER are critical to the future development of the U.S. fusion effort. It is therefore vital that the U.S. delegation to the negotiations strive for the best outcome for the program and the nation. As ITER negotiations commence, it will be necessary for the OFES, working with the fusion community, to reexamine all elements of the present and desired fusion program and to work through the difficult, often contentious, but vital process of prioritizing all parts of the program. In the absence of such a process, budget pressures and commitments to ITER could severely unbalance the program.

While the ITER process and the outcomes of the negotiations will determine a large part of the U.S. effort, this is not the only determinant when striking a new balance for the U.S. program. For instance, it is clear that a technology program without a strong science base, or a science program without a strong technology base, will leave the United States unable to build effectively on the developments coming from more advanced programs abroad as well as from ITER.

Although not directly related to a burning plasma experiment in a tokamak, some scientific issues of importance to the long-range development of the U.S. fusion program will be best addressed on nonburning facilities in tokamak and non-tokamak machines. The U.S. fusion program must continue an effort parallel to the ITER project focused on developing the scientific base for promising fusion reactor concepts.

The internationalization of fusion research is increasing with the development of the ITER project. However, the international effort is not limited to ITER, or indeed to collaborations on the large tokamaks in the global fusion portfolio. International partnerships on developing alternative fusion configurations have been and will continue to be important.

Throughout this report, the committee provides analysis of the compelling and key scientific, technical, and programmatic issues that will need to be balanced as the U.S. program progresses.

> **Conclusion:** A robust program of theory and simulation, coupled with experimental verification, is required in order to maximize the yield of scientific and technical understanding from a balanced fusion program.

Theory and simulation are essential components of understanding large-scale fusion systems and have significantly contributed to progress in understanding the behavior of fusion plasmas—for example, in the area of turbulence and nonlinear physics. Going forward, a program in theory and simulation must rely on a marriage of advances in experimental fusion science, information technology, plasma science, applied mathematics, and future developments in software.

> **Conclusion:** The recruitment, training, and retention of scientific and technical talent are crucial elements of the U.S. fusion science program.

The success of the U.S. fusion effort will depend on strong programs in plasma and fusion science. Universities have and will continue to play several critical roles, including those of maintaining the workforce supply and serving as research centers that can generate and nurture new scientific and technological ideas and that can leverage extensively the latest knowledge from other fields of science.

The committee concludes that the ramp-up to a burning plasma experiment will pose critical workforce challenges for the U.S. fusion effort. Indeed, the scientific and technical workforce in plasma and fusion science and engineering in the universities and at large fusion facilities is aging, with too few young people entering the field. There is an immediate need for technically trained personnel to build a burning plasma experiment. It is clear, therefore, that the U.S. fusion program will have to take steps to meet these critical needs.

There is a related issue regarding the viability and vitality of the university programs. These projects provide many of the new ideas and techniques and the continuing influx of talented personnel that will be needed for a burning plasma experiment and beyond in the quest for useful fusion energy. The specific projects to be pursued in the universities will change as our understanding increases, new ideas are developed, new facilities come online, and strategies involving specific concepts evolve. Nevertheless, the role that university programs play in meeting personnel needs and providing new ideas and training opportunities can be expected to continue, throughout the era of the burning plasma experiment and farther along the path to practical fusion energy.

Recommendations for a Program Strategy

The committee offers its conclusions as guiding principles for the Department of Energy as it plans to maintain a strategically balanced fusion program in support of the ITER project, aimed at maximizing the scientific and technical understanding and providing the foundation of fusion as an energy source.

It is clear that there are many unknowns as the fusion community embarks on this great scientific challenge. The elements required for the long-term health and vitality of this part of the U.S. research enterprise are not crystal clear, but this report strives to provide a strategy for the balancing of the program through its elucidation of the key scientific, technical, and programmatic issues that need to be addressed in the coming years. What is clear is that whatever strategy is adopted, it should be flexible, innovative, and inclusive in striking the required balance for success. It is with this objective in mind that the committee offers the following recommendations:

- **The United States should participate in a burning plasma experiment.**
- **The United States should participate in the International Thermonuclear Experimental Reactor (ITER). If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced U.S. fusion science program.**
- **The United States should pursue an appropriate level of involvement in the ITER program, 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.**
- **If the ITER negotiations fail, the United States should continue, as soon as possible, to pursue the goal of conducting a burning plasma experiment with international partners.**
- **A strategically balanced U.S. fusion program should be developed that includes U.S. participation in ITER, a strong domestic fusion science and technology portfolio, an integrated theory and simulation program, and support for plasma science. As the ITER project develops, a substantial augmentation in fusion science program funding will be required in addition to the direct financial commitment to ITER construction.**
- **The U.S. fusion science program should make a focused effort to meet the need for personnel who will be required in the era of the burning plasma experiment. This effort should have the following goals: to attract talent to the field; to provide broad scientific and engineering training, specialized training, and training on large devices, as required; and to revitalize the fusion workforce.**
- **Although active planning has been undertaken by the U.S. fusion community in recent years, the addition of so major a new element as ITER requires that, to ensure the continued success and leadership of the U.S. fusion science program, the content, scope, and level of U.S. activity in fusion should be defined through a prioritized balancing of the program. A prioritization process should be initiated by the Office of Fusion Energy Sciences to decide on the appropriate programmatic balance, given the science opportunities identified and the budgetary situation of the**

time. The balancing process also could be guided by multiyear budget planning that projects funding growth and should involve significant community input. The prioritization process should be organized with three elements of the fusion program in mind:

—To advance plasma science in pursuit of national science and technology goals;
—To develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and
—To pursue fusion energy science and technology as a partner in the international effort.

These program elements are indeed the three goals of the U.S. fusion program as outlined by the OFES in 1996. The committee affirms these elements as substantive and appropriate for a strategically balanced program.

The committee notes that the development of a scientifically and programmatically balanced program for fusion energy research and development must be matched with a credible and achievable funding plan. The plan should have a multiyear focus and must be cognizant of overall federal budgetary issues and likely spending constraints. With this in mind, the committee offers the following observations on the budget implications of the strategy recommended herein:

- **Undertaking a burning plasma experiment cannot be done on a flat budget.**
- **A funding trajectory for the U.S. fusion program should be developed to provide support for capturing the long-term benefits of joining the international ITER collaboration while retaining a strong scientific focus on the long-range goal of the program.**
- **A flat budget for the Office of Fusion Energy Sciences (OFES) will degrade the scientific research support in the fusion program, inevitably leading to decay in facilities and a decline in research opportunities. Overall, this approach weakens the very structures needed to optimize the benefits of the investment in the ITER program.**
- **At a minimum, in order to capture the benefits of a burning plasma experiment, augmenting the U.S. program to cover all of the U.S. ITER construction and operating costs would be required.**
- **The OFES and the fusion community will have to make serious judgments with respect to priorities in determining the activities at all stages of the U.S. fusion program.**

FINAL COMMENT

The committee concludes that the United States is ready to take the next critical step in fusion research and recommends that participation in a burning plasma experiment be implemented through participation in the ITER project as part of a strategically balanced fusion program. As the following chapters show, the opportunity for advancing the science of fusion energy has never been greater or more compelling, and the fusion community has never been so ready to take this step.

2

Scientific and Technological Value of and Interest in a Burning Plasma

INTRODUCTION

Fusion energy holds 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 that, like the center of the Sun, is heated by fusion reactions. The plasma is said to be burning when alpha particles from the fusion reactions provide the dominant heating of the plasma. 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 (D-T) fusion reactions. However, these early experiments were not large enough or powerful enough to achieve the plasma-confinement conditions for producing a fully burning plasma in which more power is released by the fusion reactions than is used to heat the plasma. In such a burning plasma, the heating of the plasma from fusion reactions is sufficiently high to strongly influence the equilibrium and stability properties of the plasma itself. These earlier D-T experiments in TFTR and JET produced fusion power output levels that were only a fraction of the total input power. The plasma heating induced by this fusion power was measurable, but well below the levels necessary to significantly influence the plasma behavior and thus enter the burning plasma regime.

No experiment has yet entered the burning plasma regime, and the physics in this self-heated regime remains largely unexplored. Table 2.1 presents a comparison of some critical parameters expected for a burning plasma experiment in the International Thermonuclear Experimental Reactor (ITER) device with the values achieved to date in D-T experiments. A burning plasma experiment would address for the first time all of the scientific and technological questions that all fusion schemes must face. Such an experiment is the crucial element missing from the world fusion energy science program and a required step in the development of practical fusion energy.

Scientific advances in the 1990s significantly improved designs for a burning plasma experiment. 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. Thus, a burning plasma experiment will take place of necessity as a tokamak.

TABLE 2.1 Comparison of Design Characteristics of the International Thermonuclear Experimental Reactor (ITER) with Achieved Conditions in Deuterium-Tritium (D-T) Experiments to Date

Parameter	ITER[a] Pulsed	ITER[a] Steady State	TFTR[b] (D-T)	JET[c] (D-T)
Radius (m)	6.2	6.4	2.5	3.0
Plasma volume (m^3)	831	770	38	153
Normalized pressure (percent)	2.8	2.8	1.1	2.6
Normalized confinement ($H_{98y,2}$)	1.0	1.6	1.3	1.6
Pressure-driven current fraction (percent)	10	48	26	10
Magnetic field strength (T)	5.3	5.2	5.6	3.5
Fusion power (GW)	0.5	0.36	0.011	0.016
Q (fusion power/power supplied)	10	6	0.27	0.64

NOTE: The normalized pressure is the ratio of the average plasma pressure to the vacuum magnetic pressure at the horizontal midpoint of the plasma.

[a] From "ITER Technical Basis," available online at http://www.iter.org/ITERPublic/ITER/PDD4.pdf. Accessed June 1, 2003.

[b] From "TFTR Machine Parameters," available online at http://w3.pppl.gov/tftr/info/tftrparams.html. Accessed July 1, 2003.

[c] From "Report on JET Activities," available online at http://www.jet.efda.org/pages/rep-of-activ.html. Accessed June 1, 2003.

Other magnetic configurations—for example, advanced tokamaks, reversed-field pinches, spherical tori, and stellarators—have potential advantages, and all have made significant progress in the past decade. The discovery that confinement can be enhanced by suppressing turbulence and then finding regimes compatible with steady-state operation has 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. A tokamak-based burning plasma experiment should produce scientific understanding and technological developments of general use for a wide range of configurations.

If it is developed and understood in sufficient detail to provide predictive capability, the scientific knowledge of burning plasmas derived from a tokamak experiment such as ITER will be transferable to other magnetic configurations. The tokamak configuration is closely related to most other leading contenders for fusion energy development, so a wide range of phenomena may be extended from the tokamak to other configurations through theory and computation in the future. These phenomena include alpha-particle confinement and transport, the interaction of alpha particles with instabilities, fusion burn control, interactions of turbulence and magnetohydrodynamic (MHD) phenomena with alpha particles, and so on. The degree to which theory and computation will allow extrapolation to other configurations will evolve with time, but it is already clear that the tools and understanding derived from research in large-tokamak experiments have influenced and in most cases accelerated the development of other members of the family of toroidal configurations. It is reasonable to assume that this influence will continue to extend the knowledge of burning plasma behavior to other attractive confinement configurations in the future.

The U.S. fusion program structure is formally defined by its mission to "advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source."[1] The program has defined three goals to achieve in pursuit of this mission:

1. Advance plasma science in pursuit of national science and technology goals;
2. Develop fusion science, technology, and plasma-confinement innovations as the central theme of the domestic program; and
3. Pursue fusion energy science and technology as a partner in the international effort.[2]

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[1] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

[2] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

While the study of burning plasmas will contribute to achieving the first two goals of the fusion science program, it is especially relevant to fulfilling the third goal listed above. Adding a burning plasma experiment to the U.S. fusion program must be considered in the context of these mission goals. To do this effectively, it is necessary to explore the critical motivations for the proposed burning plasma experiment. This chapter addresses that question by analyzing the importance of a burning plasma experiment for fusion energy science and the development of fusion energy, as well as its importance for basic plasma science, for other areas of science, and for fusion technology. Special attention is given to identifying science and technology issues that have particular relevance to the development of fusion energy. In each case, addressing the issue to a degree sufficient for developing the knowledge base for fusion energy requires that it eventually be studied in a burning plasma. For those issues that depend on the presence of a large alpha-particle population of fusion origin, a burning plasma is required. It is only in the burning plasma experiment that the full range of complex interactions between the plasma and its self-generated heat source can be confronted. For this reason, the test of plasma behavior under self-heated conditions is a critical next step for understanding fusion-producing plasmas and projecting to fusion energy production. As important, a burning plasma experiment provides the first opportunity to test many relevant fusion technologies at a reactor scale.

SCIENTIFIC IMPORTANCE OF A BURNING PLASMA FOR FUSION ENERGY SCIENCE AND THE DEVELOPMENT OF FUSION ENERGY

At each point in the development of fusion science and the implementation of new fusion facilities, new scientific regimes have been explored and important insights have been gained. The approach to the burning plasma regime by TFTR and JET provides a critical example; in these experiments, fusion plasmas were created transiently and with insufficient self-heating to burn, but significant new physics was still uncovered. It is expected, therefore, that a burning plasma experiment at the near-reactor scale will present new scientific opportunities that must be explored and understood. In particular, it can be expected that a burning plasma experiment, owing to its unique plasma parameters and its ability to study these issues in the burning state, will make critical contributions to understanding the following:

- Plasma behavior when self-sustained by fusion (burning),
- Fusion-plasma turbulence and turbulent transport,
- Stability limits to plasma pressure,
- Control of a sustained burning plasma, and
- Power and particle exhaust.

Subsections below address each of these areas in greater detail; each closes with an italicized finding relating the science opportunities to fusion energy science and the development of fusion energy.

Behavior of Self-Sustaining Burning Plasmas

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 if the alpha particles are well confined. The fusion rate increases approximately as the square of the plasma pressure, in the expected temperature range. This nonlinear heating will combine with the turbulent confinement of the plasma to modify the plasma equilibrium and behavior. Under some conditions 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. In the D-T experiments on TFTR and JET, these instabilities were observed at low amplitude with alpha particles in specially designed experiments (see Figure 2.1). However, the larger size of a burning plasma experiment is predicted to significantly change the spectrum of unstable Alfvénic fluctuations when they occur, generating turbulence and possibly increasing alpha-particle losses. Understanding these complex interactions between large populations of fusion-produced alpha particles and the plasma equilibrium and stability is a critical integrating step in developing the knowledge base for fusion energy. Developing and validating such an understanding require access to a sufficiently large fusion-producing plasma environment. Plasma regimes with these parameters are not accessible in present experiments.

Developing and experimentally validating a theory of these Alfvénic fluctuations under conditions of possibly turbulent spectra present a complex and scientifically challenging problem. It will be advantageous to do so in a flexible experiment in which the stability boundary can be challenged in a controlled manner. Linear stability analyses of these instabilities for ITER conditions indicate that they will be marginally stable under normal operating conditions, and hence they should not prevent access to the expected burning plasma regime. However, operating at higher electron temperatures in advanced operation regimes may allow a

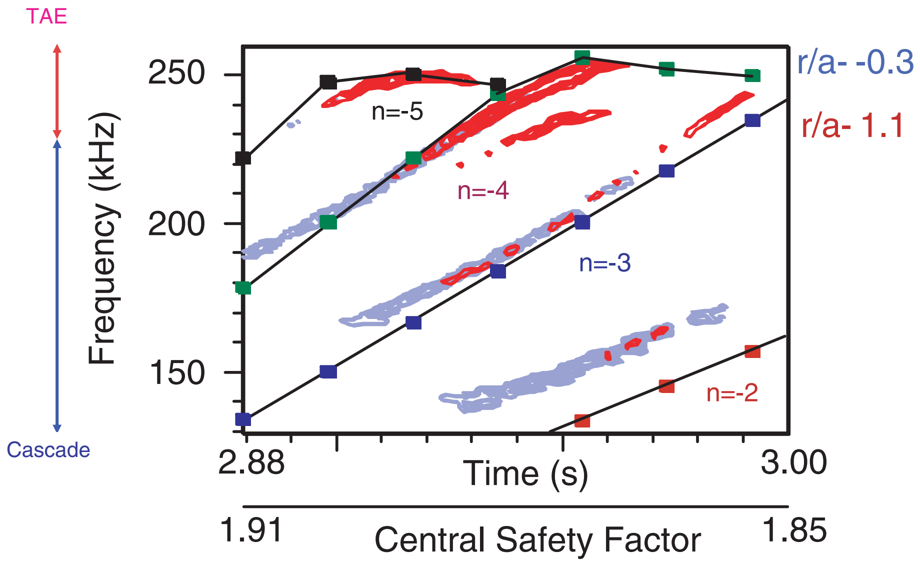


FIGURE 2.1 Frequency evolution of Alfvénic modes driven by fusion alpha particles in the Tokamak Fusion Test Reactor deuterium-tritium experiments as the central plasma current evolves. Blue contours: reflectometer measurements of mode amplitude inside the plasma. Red contours: magnetic measurements of mode amplitude at the plasma edge. Solid squares connected by lines: predicted frequency evolution from the CASTOR and NOVA-K computer modeling codes using experimental conditions, showing evolution from the cylindrical cascade Alfvén mode to the toroidal Alfvén eigenmode (TAE). Courtesy of R. Nazikian, Princeton Plasma Physics Laboratory.

challenge to the stability boundary and allow excitation of these modes. ITER will thus provide a unique opportunity to study these modes in a controlled manner and to provide critical tests of emerging theory.

> *The behavior of an energy-producing fusing plasma will be dominated by the complex nonlinear interactions between plasma heating, stability, and confinement in a plasma heated by the fusion reactions and can only be studied in an integrated manner for the first time in a burning plasma experiment.*

Fusion-Plasma Turbulence and Turbulent Transport

A burning plasma experiment will greatly improve the extrapolation of our knowledge of plasma turbulence and turbulent transport from present experiments to the effective size of an energy-producing reactor. The effective plasma size (physical size divided by ion magnetic-gyroradius) must be increased by a factor of 3 to 4 in order to achieve burning conditions; this can be accomplished by increasing either the actual plasma size or the magnetic field strength. It is predicted that an increase in effective plasma size at high plasma temperature will modify many phenomena already studied in existing experiments, such as the saturation of turbulence-generated transport and the onset of macroscopic (tearing) instabilities. Additionally, transport studies in the regime where electron and ion temperatures are comparable (owing to electron heating and equilibration) become possible. These phenomena can determine the plasma pressure that can be confined and thus the level of fusion power produced.

> *Extending the knowledge of plasma confinement and turbulent transport to relative plasma sizes several times larger than those presently available, into the range required for an energy-producing plasma, is necessary for developing a predictive capability of fusion-plasma performance.*

Stability Limits to Plasma Pressure

Since the fusion power produced by a burning plasma increases quadratically with the plasma pressure, maximizing the pressure is crucial for achieving a fusion-heated and fusion-sustained plasma. In tokamaks, the maximum pressure is limited by plasma instabilities. The designs for the proposed burning plasma experiment build on the understanding of these instabilities developed from existing tokamak experiments, such as methods to increase the pressure limits using plasma shaping, control of plasma profiles, and external feedback systems. A burning plasma experiment will test this understanding at larger effective plasma size and in the presence of a substantial alpha-particle population. This study will be especially interesting, because strong self-heating by well-confined alpha particles will control the pressure profile evolution, possibly reducing the effectiveness of existing external control tools. The behavior of the pressure stability limit with strong self-heating may thus lead to the development of new strategies for plasma profile control. Such strategies will be important for validating the basis for the further development of fusion energy.

> *Understanding the interactions between large-scale plasma instabilities and a large, fast alpha-particle population in the presence of strong self-heating is critical for devising effective control strategies and optimizing fusion power production.*

Controlling Sustained Burning Plasmas

A fusion reactor should operate in steady state, minimizing the recirculating power (maximizing the energy gain). In the steady-state advanced tokamak configurations that are envisioned, most of the plasma current is self-generated by the pressure (the "bootstrap current"). In a burning plasma, the heating of the plasma will also depend on the plasma pressure. Furthermore, the distribution of current within the plasma has a large effect on the confinement properties and the stability limit for the plasma pressure. Thus, heating, pressure, and current are coupled so that these configurations are nonlinear and self-organized. Achieving and controlling such a self-organized plasma configuration in a burning condition will be an exciting challenge. Meeting this challenge will require the development of new diagnostics, theoretical and computational models, and feedback control methods.

> *Developing an understanding of and the ability to control sustained, self-organizing burning plasmas is needed in order to specify engineering requirements for energy-producing plasmas and to develop attractive advanced fusion concepts.*

Power and Particle Exhaust

An energy-producing fusion system must not only generate sufficient fusion power, it must also absorb the generated energy at the walls of the device without deleterious effects and provide for elimination of the helium ash. For example, in ITER the total power transported out of the plasma will be about 100 MW, and the helium ash content must be kept below about 5 percent. The heat flow to the divertor must be reduced using impurity radiation, but these impurities must not be allowed to transport into the core plasma, where they would reduce fusion reactivity and increase radiative losses. In addition, instabilities in the plasma edge—known as edge-localized modes—may transiently increase the heat load on the divertor plates to a significant degree; this effect will need to be accommodated. The ITER experiment will explore this challenging issue at the larger scale and power level of a burning plasma.

> *The effective control of heat flow to the chamber walls of the device for sustained operation and control of plasma composition are critical to future fusion concepts and will be tested under more reactor-relevant conditions in the burning plasma experiment than in experiments to date.*

Conclusion

A burning plasma, whose equilibrium and stability properties can be strongly influenced by the presence of fusion-produced alpha-particle heating, offers an environment for the study of several discrete scientific phenomena that influence or are influenced by the alpha heating power. These include the propagation of the fusion burn itself, plasma turbulence and its associated transport at the larger scale of a fusing plasma, pressure limits, sustainability, and the complex interactions in the plasma–wall interface region. While each issue offers unique scientific challenges, it is the integration of all of these phenomena in a complex, self-organizing system with its own heat source that is the overriding and most compelling aspect of the study and understanding of a burning plasma. Indeed, it is only in the burning plasma experiment that these strongly nonlinear and interacting phenomena can be realized simultaneously. In that context, it is important that the burning plasma experiment have sufficient flexibility to modify the susceptibility to these various nonlinearities so that their respective influences on the aggregate behavior of the burning plasma system can be reasonably isolated and tested.

SCIENTIFIC IMPORTANCE OF A BURNING PLASMA FOR BASIC PLASMA PHYSICS

Basic plasma physics—the study of fundamental processes in the plasma state of matter—is relevant to a variety of fields, including space plasmas, industrial plasmas, astrophysics, and fusion. A burning plasma experiment entails specific scientific goals of great importance to fusion power. It is thus designed specifically to investigate the burning plasma state and cannot replace experiments that are purpose-built to directly address the broader set of basic plasma issues. However, a burning plasma experiment and the scientific program that leads to and supports it may make useful contributions to the basic understanding of plasmas. This section explores this possibility by considering the following four fundamental plasma processes, which are not yet fully understood, and their role in the burning plasma experiment:

- Magnetic field line reconnection,
- Plasma turbulence,
- Abrupt plasma behavior, and
- Energetic particles in plasmas.

Magnetic Field Line Reconnection

Magnetic field line reconnection is the process by which magnetic topology changes sometimes suddenly. Reconnection is often accompanied by the generation of fast particles and flows, the sudden release of energy in heat and waves, and nonlocal changes in plasma resistivity and turbulence. Reconnection is believed to be a key process in solar flares, magnetospheres, and astrophysical processes. Several basic reconnection experiments have been performed in the past, representing first steps in forming a greater understanding of the phenomenon, but much is still unknown. It is expected that tearing modes, disruptions, and sawtooth oscillations will be seen in a burning plasma experiment; they may limit the accessible plasma pressure. These phenomena all involve at least some reconnection of field lines. Careful diagnosis of these phenomena will contribute to our understanding of reconnection. The codes developed to model reconnection in the burning plasma experiment will be immediately useful in simulating reconnection in space and astrophysics.

Plasma Turbulence

Plasma turbulence is now under intense investigation both numerically and in laboratory experiments (see Figure 2.2). Turbulence in fusion devices dominates the transport of heat, and the minimizing of turbulence is a major goal of fusion science. Plasma turbulence also controls the behavior of accretion disks around black holes and the dynamics of the solar corona. The discovery that shear flows suppress turbulence in tokamaks is a fundamental advance in understanding, as well as a practical method for increasing the performance of the burning plasma experiment. Since this suppression is key to the desired high-confinement mode (H-mode)—as well as to discharges with internal transport barriers—it is being investigated extensively. Turbulent transport of heat by electrons is less well understood than transport by ions. This issue will also be addressed extensively by a burning plasma experiment, and it is hoped that the experiment will lead to a better fundamental understanding of the interaction between turbulence on different scales. Gyrokinetic simulation, which was developed to simulate the turbulence and predict the performance of fusion plasmas, has found a wide range of application to basic plasma physics. The demands of simulating turbulence in the burning plasma experiment will undoubtedly lead to improved computational algorithms that will find subsequent use in other areas of plasma science.

Abrupt Plasma Behavior

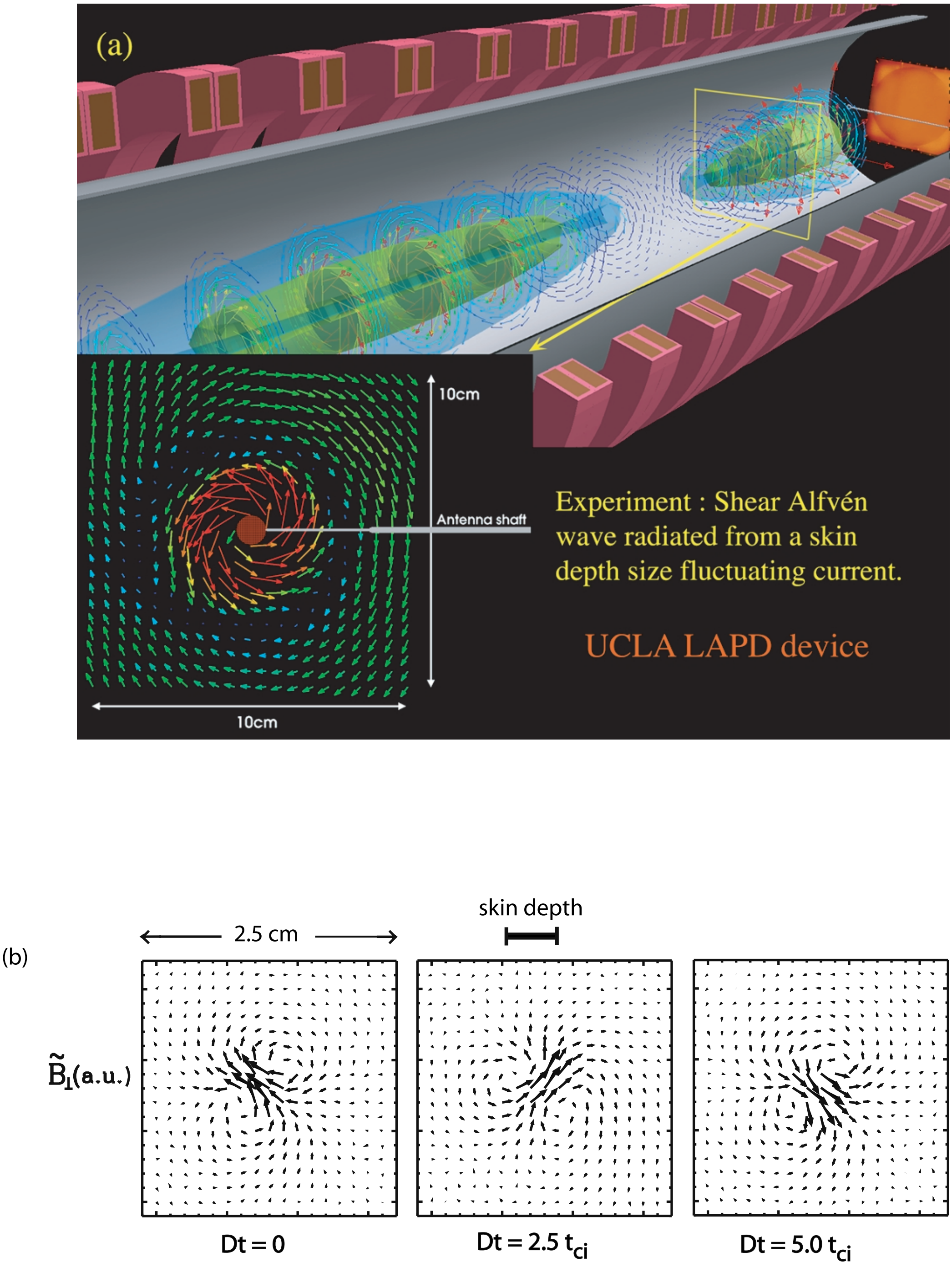
Many plasmas exhibit abrupt changes in behavior. Examples include solar flares, disruptions in tokamaks, flux ropes, coronal mass ejections, and magnetic substorms (see Figure 2.3). Very little is understood about these processes. Disruptions at the pressure limit in a burning plasma experiment are extremely problematic, as they can cause damage to the walls of the device. Although the physics of disruptions and edge-localized modes (ELMs) is not fully understood, their phenomenology is. Thus, avoidance of their most serious consequences is expected. One can expect some such events, however, and the data from these events will help unravel the mysteries of abrupt plasma behavior.

Energetic Particles in Plasmas

Burning plasmas by definition have a significant population of fast alpha particles. Many naturally occurring plasmas also have an energetic component—cosmic rays in the Galaxy and ring current protons in the magnetosphere, for example. Energetic particles (such as those from an avalanche of runaway electrons in a fusion plasma) can drive instabilities, including the toroidal Alfvén eigenmodes (TAE) observed in tokamaks and discussed in the subsection above entitled “Magnetic Field Line Reconnection.” Clearly, the burning plasma experiment will contribute greatly to our understanding of such plasmas.

Conclusion

In summary, it is clear that the burning plasma experiment will contribute to many areas of basic plasma science. In essence, a burning plasma program’s benefits to basic plasma physics will be threefold. First, critical phenomena in the burning plasma involve fundamental plasma processes. These phenomena will be studied in the burning plasma experiment and the supporting parts of the base program, as discussed above. Second, the burning plasma scientific program will develop tools—for example, computer codes for analysis—that will be of use to basic plasma science. Third, it is highly likely that new issues will arise from the studies on the burning plasma experiment. They will motivate new theoretical activity and focused investigations on nonburning experiments to develop and confirm a detailed understanding of the basic processes. However, the extreme conditions in a burning plasma experiment and other large fusion experiments make any detailed measurement a challenge. Notwithstanding the promise of a burning plasma experiment in increasing our understanding of plasma science,


(a)
10cm
Antenna shaft
10cm
Experiment : Shear Alfvén wave radiated from a skin depth size fluctuating current.
UCLA LAPD device
(b)
2.5 cm
skin depth
$\tilde{B}_\perp$(a.u.)
Dt = 0
Dt = 2.5 t_{ci}
Dt = 5.0 t_{ci}

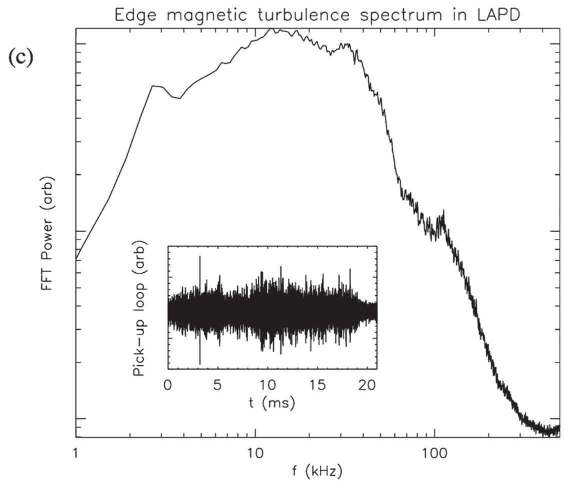


FIGURE 2.2 Edge plasma turbulence is composed of the superposition of many waves—a combination of both drift and shear Alfvén waves; the waves have correlation lengths on the order of the skin depth perpendicular to the magnetic field and much longer correlations along the direction of the magnetic field. Under controlled studies in the laboratory, one can produce single waves of either type to understand their evolution and propagation; by understanding the components of edge turbulence in detail, significant insight into the full turbulent process has been gained. In this figure, results from the Large Area Plasma Device (LAPD) experiment at the University of California at Los Angeles are shown. (a) The measured magnetic field of a shear Alfvén wave launched from a fluctuating current on the order of the skin depth in radius. The antenna is a small mesh disk inserted on a radial shaft (in the upper right). The figure shows the magnetic field of the wave in two green and blue isosurfaces and as a vector field. Each "cigar-shaped" pattern is a half wavelength long; the magnetic field of the wave is zero on axis. The data are superimposed on a model of the interior of the LAPD device. The wave data have been scaled by a factor of 2 in the radial direction for easier viewing. The inset shows the wave magnetic field at one instant of time on a plane perpendicular to the background magnetic field. The disk antenna is superimposed in the figure but is 1.54 m from this plane. Note that the vectors switch direction along a radial cut. This is because the wave has a finite perpendicular component of the wave vector, which, in turn, gives it a parallel electric field. (b) In three snapshots of time (*Dt*), the measured magnetic field of a drift Alfvén wave that was caused by a channel of field-aligned hot electrons with a radius on the order of the skin depth. The fluctuations have the shear mode polarization and rotate in the electron diamagnetic drift direction. In this case the magnetic field fluctuations are associated with a density fluctuation, which has the shape of a rotating spiral. (c) Measurement of magnetic turbulence on the edge of the LAPD plasma. The fluctuations below 2 kHz are correlated with density fluctuations and are believed to be drift Alfvén modes; the remainder of the spectrum is that of shear Alfvén waves. SOURCES: Courtesy of W. Gekelman, University of California at Los Angeles. (a) W. Gekelman, S. Vincena, D. Leneman, and J. Maggs, "Laboratory Experiments on Shear Alfvén Waves and Their Relationship to Space Plasmas," *J. Geophys. Res.*, 7225-7236 (1997); (b) A. Burke, J. Maggs, and G. Morales, "Experimental Study of Fluctuations Excited by a Narrow Temperature Filament in a Magnetized Plasma," *Phys. Plasmas*, 1397-1407 (2000); (c) data courtesy of T. Carter, University of California at Los Angeles.

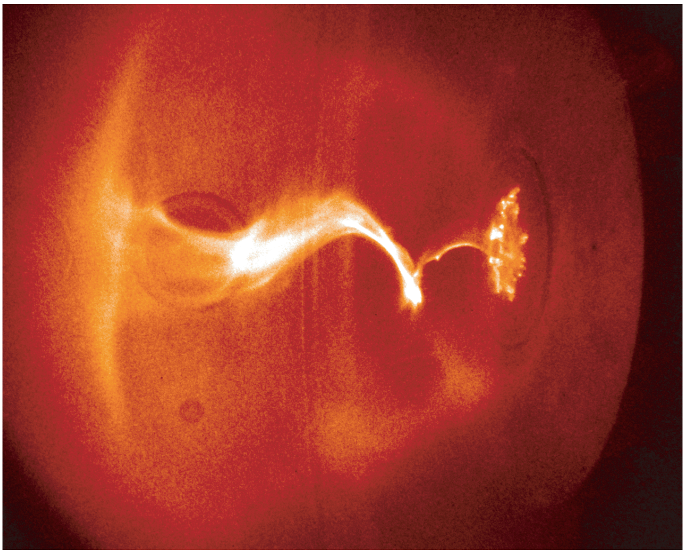


FIGURE 2.3 Kink instability of the central column produced in spheromak formation experiment at the California Institute of Technology. This kink, believed to be intrinsic to spheromak self-organization, occurs when the jetlike central column becomes sufficiently long to satisfy the Kruskal-Shafranov instability threshold. It can also be considered as a good simulation of the kink instability of an astrophysical jet. Courtesy of S.C. Hsu and P.M. Bellan, California Institute of Technology.

systematic studies of any basic process are best done on the smallest or simplest laboratory devices that can access the appropriate regime.

GENERAL SCIENTIFIC IMPORTANCE OF A BURNING PLASMA

Progress in plasma physics, and fusion-plasma physics in particular, can lead to progress in other subfields of physical science. A burning plasma experiment will likely lead to progress in new regimes. There will undoubtedly be unexpected discoveries as well; only a few examples of such connections are mentioned here.

Astrophysics and space science are replete with evidence that heat, magnetic flux, and angular momentum are transported much more quickly than is predicted by straightforward physics.[3] Enhanced transport leads to dramatic energy

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[3] National Research Council, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, Washington, D.C.: The National Academies Press, 2003.

release events such as solar flares, geomagnetic substorms, and x-ray emissions from the vicinity of black holes. On the basis of data, theory, and advanced numerical methods, laboratory plasma physics has already led to substantial insights into these processes. Burning plasmas will generate the highly energetic ions and large temperature gradients that characterize many astrophysical systems and will provide the opportunity to study enhanced transport under these more realistic conditions.[4]

Another example of general scientific interest in burning plasma physics is self-organization, which occurs in many astrophysical, space, and geophysical settings. Self-organization is characterized by phenomena on small spatial scales acting in concert to produce phenomena on large scales. One example is large-scale planetary and solar flows driven by small-scale turbulence; another is large-scale magnetic fields driven from small-scale motions. The large-scale rotational flows observed in laboratory plasmas share many common features with these self-organized flows in nature, as do the large-scale, self-sustained magnetic fields observed in some laboratory plasmas. A burning plasma experiment would offer an opportunity to observe self-organization in a new setting, with much stronger drivers and correspondingly weaker external constraints than in experiments to date.

Another set of applications involves shared diagnostic techniques rather than shared phenomena. Innovative techniques for image reconstruction can be used in many fields, including medical imaging and surface science. Probes in burning plasma must operate in a hostile environment similar to conditions in space and industrial settings.[5] Spectroscopy of heavy and highly charged ions in a burning plasma faces issues similar to those in astrophysical observations and often uses similar instrumentation.

> *A burning plasma experiment can offer substantive and important contributions to other fields of science connected to plasma physics, primarily through experimental access to the fundamental and/or extreme conditions offered by such a state.*

TECHNOLOGICAL IMPORTANCE FOR FUSION ENERGY SCIENCE AND THE DEVELOPMENT OF FUSION ENERGY

The previous sections have considered the scientific importance of a burning plasma experiment. The most compelling scientific importance is, for obvious

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[4] National Research Council, *The Sun to the Earth–and Beyond*, Washington, D.C.: The National Academies Press, 2003.

[5] National Research Council, *Plasma Science: From Fundamental Research to Technological Applications,* Washington, D.C.: National Academy Press, 1995.

reasons, the advancement of fusion energy science. What, however, is the importance of a burning plasma experiment, such as ITER, to the technological advance of fusion energy? This question is explored below with regard to the following issues:

- Breeding blanket development,
- Tritium processing,
- Magnet technology,
- High-heat-flux component development, and
- Remote handling technology.

Breeding Blanket Development

A burning plasma experiment could provide the opportunity to test and evaluate the performance of prototypical blanket modules. The blanket in a reactor is the structure immediately surrounding the plasma. It is typically about 1 m thick and is fabricated in modules designed to be remotely replaceable several times during a fusion plant's lifetime. The blanket serves the multiple functions of removing most of the energy from the fusion-produced 14-MeV neutrons, providing adequate shielding for the vacuum vessel and magnets and breeding tritium via interaction of the neutrons with lithium. The coolants used for a fusion reactor need to operate at high temperature in order to optimize plant efficiency—both for plants intended to produce only electricity and for plants that could produce both electricity and hydrogen.

The principal nondefense source of tritium is the Canadian Deuterium Uranium (CANDU) reactors. While the Canadian supply is expected to be adequate for providing the fuel for the ITER experiment without additional breeding, any fusion reactors beyond ITER must clearly produce and recover more tritium than is burned if fusion energy is to be viable.[6] A blanket providing this function is a critical fusion technology; it must be developed on ITER to ensure a tritium fuel supply for future fusion facilities.

A burning plasma experiment of the scope of ITER provides the opportunity to evaluate the tritium-breeding ratio and extraction process, the thermome-

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[6] Any arrangement to use Canadian tritium would of course have to be negotiated between ITER management and the Canadian government. Another possible source of tritium would be the target devices being developed for providing tritium for the U.S. weapons program using commercial reactors. However, this approach is still being developed for what probably are the small amounts needed for defense purposes and would have to be examined when and if that program became successful.

chanical performance, and the plasma compatibility of near-full-scale test blanket modules. In particular, the 3,000-s pulse length available in the second stage of ITER operations is well in excess of all relevant plasma time constants and is sufficiently long to ensure that all in-vessel components, including blanket test modules, come to thermal equilibrium. This is adequate for testing the breeding and thermomechanical performance of 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 development and testing. The fluence—that is, the integrated neutron flux—in the burning plasma experiments under consideration will be too low (by as much as two orders of magnitude) to explore the lifetime characteristics of materials and components needed for a reactor. The main structural material specified for ITER construction is 316L(N) stainless steel. This is not considered to be a low-activation material, but the change in its structural properties due to the neutron fluence over ITER's lifetime is well characterized and small enough that the machine's structural integrity will not be challenged. It should be noted that neither the evaluation of blanket performance under fusion reactor neutron fluences nor the evaluation of materials lifetime for reactors is part of the ITER mission. Future dedicated facilities may be needed for this purpose.

> *The development of efficient and robust reactor blanket modules is required in order to provide a means of extracting energy from the plasma, to breed the required fuel, and to provide shielding of external subsystems in future reactor concepts. A burning plasma experiment provides the first opportunity to test such blanket concepts.*

Tritium Processing

Most of the fuel injected into a fusion reactor will not be burned in a single pass. Unburned deuterium and tritium will be continuously transported to the plasma edge, where it must be collected; stripped of impurities; separated into deuterium, tritium, and hydrogen isotopes; and then reinjected as fresh D-T fuel. Elements in the fuel-processing system such as the step of separating into isotopes have already been developed on a small scale. The fuel-recovery system designed for ITER would operate online under quasi-steady-state conditions using technology that would be prototypical of that needed for a reactor. The successful demonstration of an integrated steady-state fuel-processing capability in ITER would therefore establish this technology at the reactor scale.

A related issue concerns the level of tritium inventory in the plasma chamber of a fusion reactor. Owing to its superior heat and thermal shock characteristics, carbon has been the first-wall material used in most tokamak experiments (including the "large tokamaks" TFTR, JET, and the Japanese JT-60U) during the past decade. In a process known as co-deposition, hydrocarbons form in the interaction of plasma with the wall, leading to a buildup of hydrogen in thick films deposited on components within the plasma chamber. In ITER, this could result in a limit of 10 to 100 shots before the tritium in the chamber reaches the maximum permitted by the in-vessel tritium inventory. Of necessity, a burning plasma experiment must address this problem either by excluding carbon from being the choice of first-wall material or by developing techniques to mitigate the formation and/or retention of the hydrocarbon films.

> *The control and recycling of the tritium fuel, while minimizing the tritium inventory in the plasma chamber, will be required for the routine operation of a burning plasma experiment, similar to requirements for the routine operation of future reactors.*

Magnet Technology

The superconducting magnets required for ITER are of unprecedented size and scale, being comparable to those foreseen to be required for a fusion reactor. Their development will not only continue the advances being made in niobium tin (Nb_3Sn)-based magnets but could also stimulate the research and development of magnets using still more advanced conductors and cable design. Higher field, higher current density, and higher-temperature operation can all contribute to improving the economic projections for fusion energy.

A result of the production of hundreds of tons of Nb_3Sn superconducting strand for ITER could be the development of a worldwide industrial capacity that would lower the cost and improve the performance and quality of this high-field superconductor. The U.S. fusion program has been coordinating Nb_3Sn development efforts with the U.S. High Energy Physics program. The development of about 30 metric tons of Nb_3Sn strand for the ITER Engineering Design Activity (EDA) model coil programs in the 1990s resulted in an immediate increase in both performance and production capacity. The U.S. High Energy Physics program has since advanced this type of strand performance significantly for its application to very high field accelerator magnets, such as those required for the Very Large Hadron Collider. The extremely large-scale production of Nb_3Sn required for ITER would result in significant improvements in worldwide industrial production capacity and in the quality of this superconductor, and the costs would be lowered as a result of high-volume production. This development would directly benefit the High Energy Physics program and would also allow for improved and low-cost advanced superconducting wire for many other high-field magnet applications, such as those used in high-field research magnets—for example, for nuclear magnetic resonance.

> *The ability to construct efficient high-field superconducting magnets will directly impact the economic prospects of a fusion reactor. The construction of such magnets for ITER can help drive this technology for fusion and other applications.*

High-Heat-Flux Component Development

Burning plasma experiments will need to develop high-heat-flux components; in the operating phase they will serve as testbeds in which to evaluate the performance of these 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. Handling the heat loads requires the 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. However, as in the case of materials testing, the burning plasma devices under consideration will not have the integrated operating time necessary to qualify key internal components for use in a demonstration reactor.

> *Deploying technology to handle the high-heat fluxes in a burning plasma will allow tests of these components at the reactor-heat levels expected in a fusion environment.*

Remote Handling Technology

In a fusion reactor, it is critical that the first wall and high-heat-flux components as well as ancillary components such as radio-frequency 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 remote handling tools to minimize lost experimental time owing to component failure. Prototypes of the tools exist; a burning plasma experiment would provide an integrated demonstration of their reliability and effectiveness.

> *The development and use of remote maintenance capabilities are necessary for both a burning plasma experiment and a future reactor. The burning plasma experiment will provide unique tests of these technologies in a fusion environment.*

Conclusion

A burning plasma experiment such as ITER could offer an early opportunity to begin the development of essentially all of the 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.

3

Readiness for Undertaking a Burning Plasma Experiment

This chapter describes the present state of readiness of the fusion community to undertake a burning plasma experiment. Key criteria that define scientific and technical readiness are identified, and the present state of readiness with respect to each of these criteria is discussed. In analyzing the readiness issues, the ITER design is used as a prototypical example of the burning plasma experiments under consideration; relevant differences for other designs are noted.

A successful burning plasma experiment will provide the opportunity to address most, if not all, of the scientific and technical issues discussed in Chapter 2. With the goal of addressing all of the critical issues in mind, the committee formulated criteria for scientific and technical readiness to proceed with a burning plasma experiment. To say that a criterion is satisfied effectively states that its critical scientific and technical issues can be addressed in the proposed experiment with a reasonable degree of confidence. In the spirit of a scientific experiment, readiness to proceed does not guarantee the performance of the burning plasma under all conditions, but only the accessibility of the desired regime.

The focus of this discussion is on evaluating the readiness to realize an experiment to study the scientific and technical issues identified as important to fusion energy science and the eventual development of fusion energy. But in addition, it is clear that confronting these issues in a burning plasma experiment will provide significant opportunities for addressing the issues of importance to the understanding of plasma physics and physical science in general.

SCIENTIFIC READINESS

The committee found it useful to assess the scientific readiness to undertake a burning plasma experiment in terms of the following six well-defined criteria:

1. Confinement projections,
2. Operational boundaries—plasma pressure and current,
3. Mitigation of abnormal events,
4. Maintenance of plasma purity,
5. Characterization techniques, and
6. Plasma control techniques.

It is the committee's judgment that each of these six scientific areas must be sufficiently understood before a burning plasma experiment can be positioned for success. Each of these criteria is discussed and analyzed below. As a whole, this analysis allows for an estimate to be made of the state of readiness for undertaking a burning plasma experiment.

Confinement Projections

Reaching the burning plasma regime depends critically on the rate at which energy is lost from the plasma. This energy-loss rate can be projected on the basis of confinement scaling, scaling with similar nondimensional parameters, or models of the plasma transport averaged over magnetic-flux surfaces. Each of these methods of projecting energy-loss rates predicts that ITER will meet the goal of producing 10 times more power via fusion reactions in the plasma than the input power used to heat the plasma (i.e., $Q = 10$).

It is possible to predict accurately the energy-loss rate in existing tokamak experiments through confinement scaling studies that fit the observed energy confinement time τ_E (where τ_E is the reciprocal of the energy-loss rate from the tokamak global database of about a thousand discharges in eight large tokamaks) as a power law in the appropriate discharge parameters. The validity of this technique has been confirmed by results from the new-generation tokamaks. An extrapolation of the energy confinement time by a factor of approximately 3 is required to go from the best confinement time in present large tokamaks to ITER. A relevant measure of fusion performance is the "fusion triple product," $nT\tau_E$, which is roughly proportional to the fusion gain factor, Q. Figure 3.1 displays this fusion triple product for tokamak discharges as a function of the value predicted by the scaling analysis. The present database spans three orders of magnitude in $nT\tau_E$. An extrapolation by an additional factor of 20 is required to reach the nominal ITER operating point corresponding to a fusion gain $Q = 10$.

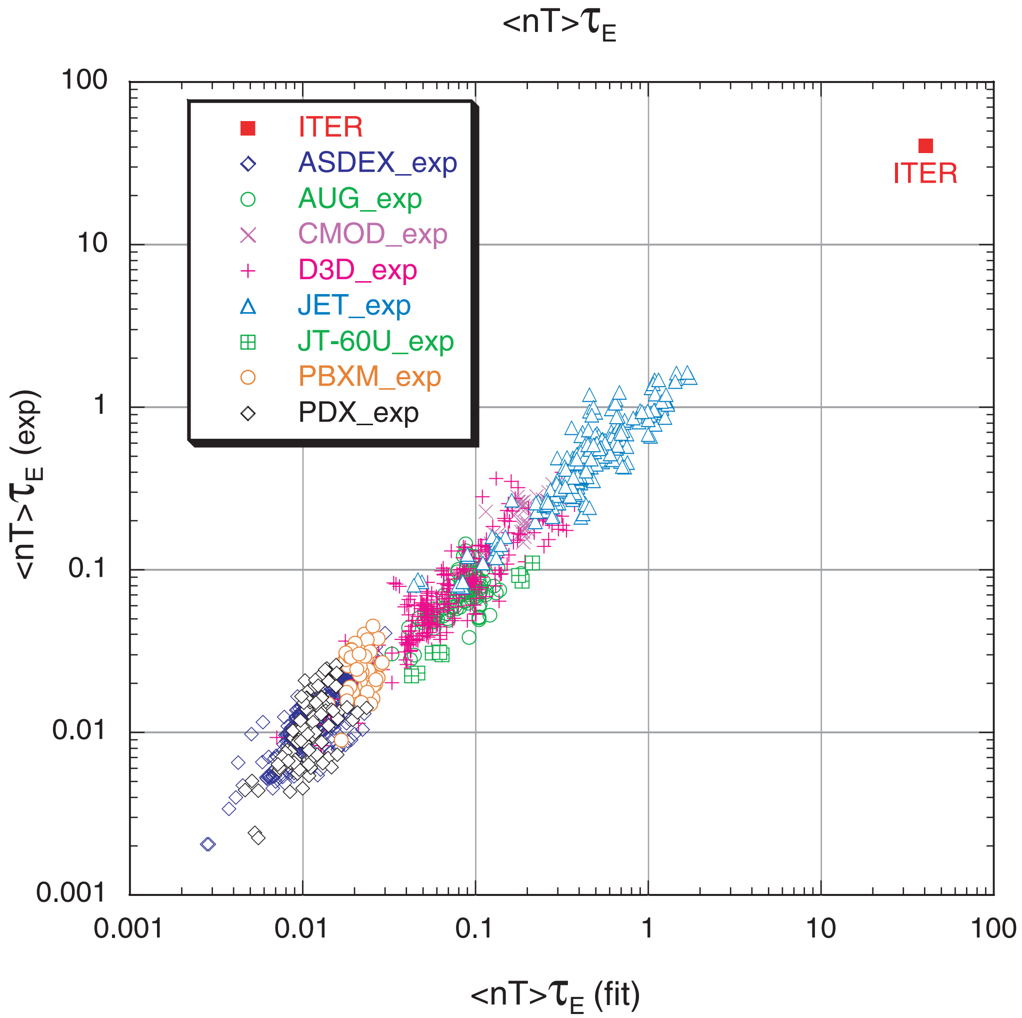

FIGURE 3.1 The fusion triple product, $nT\ \tau_E$, in units of 10^{20} keV-s/m^3 from actual experimental discharges versus that projected by confinement scaling studies. Data presented are taken from the International Tokamak Physics Activity (ITPA) high-confinement mode (H-mode) database, the international tokamak database for enhanced confinement discharges similar to those expected in ITER, provided by the ITPA Confinement Database and Modeling group. Note that only results from those experiments that could access this enhanced confinement regime are included in this data compilation. NOTE: Symbols on plot are defined as follows: ITER—International Thermonuclear Experimental Reactor; ASDEX—Axially Symmetric Divertor Experiment; AUG—ASDEX Upgrade Project; CMOD—Alcator C-Mod Tokamak Fusion Research Project; D3D—DIII-D National Fusion Facility; JET— Joint European Torus; JT-60U—flagship tokamak of Japanese magnetic-confinement program; PBXM—Princeton Beta Experiment Modification; and PDX—Poloidal Divertor Experiment. Courtesy of J. DeBoo, General Atomics, and F. Perkins, Princeton Plasma Physics Laboratory.

Scaling with similar nondimensional parameters makes use of the fact that existing tokamaks can simultaneously match all important nondimensional parameters projected for burning plasma discharges, other than the nondimensional size parameter ρ^*, which is the ratio of the ion gyroradius to the plasma minor radius. In present experiments, ITER-like values of this parameter cannot be achieved simultaneously with the requisite constraints on the normalized plasma density. The scaling of the energy-loss rate with this size parameter is then inferred by comparing discharges with different values of ρ^* in which the remaining nondimensional parameters are held fixed at the values expected in the burning plasma experiment. While this analysis has not been done for the current ITER design, the resulting projection of the confinement time with ρ^* nearly matches the projection from the global database scaling for the previous ITER design (i.e., the ITER-Engineering Design Activity).[1]

These scaling studies provide confidence that the energy confinement in ITER will be sufficient to obtain a fusion gain, $Q \geq 5$. The extrapolation from the existing database to the near-reactor conditions accessible in ITER is comparable to the step taken in moving from the midsize experiments in the 1980s to the large tokamaks now in operation. The performance of these existing tokamaks was accurately predicted by the previously existing database. The projections for ITER are able to make use of both considerably refined data from the present generation of large tokamaks and the physics-based dimensionless-parameter scaling technique.

Models based on analyses of plasma instabilities and three-dimensional simulations of fully developed microturbulence can now predict ion thermal diffusion in the plasma core. These transport models have been extensively benchmarked against experimental results.[2] Generally, these models reliably predict the thermal transport and the resulting core temperature profiles when provided an appropriate boundary temperature, albeit under conditions in which the ions are hotter than the electrons—in contrast to the situation expected at ITER. At present, there is a lack of adequate theoretical models to predict the temperatures near the plasma boundary, so this parameter is taken from empirical fits to experimental data. While this uncertainty in the edge temperature introduces some uncertainty in the projected fusion gain, the transport models project performance for ITER similar to that predicted by the scaling studies—namely, that ITER will achieve a fusion

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[1] ITER Physics Expert Groups, "ITER Physics Expert Groups on Confinement and Transport and Confinement Modeling and Database," *Nucl. Fusion* **39** (12), 2175. See §7.3, p. 2211.

[2] R.E. Waltz, G.M. Staebler, W. Dorland, G.W. Hammett, M. Kotschenreuther, and J.A. Konings, "A Gyro-Landau-Fluid Transport Model," *Phys. Plasmas* **4**, 2482 (1997).

gain in the range $5 \leq Q \leq 15$.[3] This analysis of plasma confinement provides an acceptable level of confidence in projecting the performance of ITER.

It is possible that in a burning plasma experiment, new (e.g., nonlinear) interactions will be discovered between the fusion-produced fast alpha particles and the plasma equilibrium and that such interactions could alter the confinement properties of the plasma. A key goal of conducting a burning plasma experiment is to investigate the particle and energy transport in this potentially new regime.

> *The present level of uncertainty in confinement projections is acceptable for proceeding with a burning plasma experiment.*

Operational Boundaries—Plasma Pressure and Current

Tokamak operation is constrained by limits on the plasma pressure and current. Such limits can be calculated within ideal magnetohydrodynamic (MHD) theory and can be avoided through control of the plasma pressure and current. ITER will operate within these limits. Experiments are planned to explore the boundary of this stable regime with the goal of further expanding the burning plasma operating regime. These experiments will be guided by the results of computational models that include dissipative effects and follow the growth and saturation of MHD instabilities at the boundaries of the stable operating regime. Examples of this MHD modeling capability are shown in Figures 3.2 and 3.3. Such modeling contributes to an understanding of whether the consequence of violating a particular operational boundary will be a degradation in performance or a catastrophic loss of confinement followed by a disruption of the plasma current.

Within this stable operating regime, there is another instability, called the neoclassical tearing mode, that can degrade plasma performance. This instability depends strongly on the dissipation and transport properties of the plasma. Although the theory for the neoclassical tearing mode is still developing and the 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-drive capabilities in ITER is expected to provide a means of stabilizing these modes, should that prove necessary (see Figure 3.4).

There is a limit to the plasma density that is proportional to the plasma current, and it is characterized empirically. It is planned that ITER will operate below

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[3] J.E. Kinsey et al., paper presented at 19th International Atomic Energy Agency Fusion Energy Conference, Lyon, France, 2002 (*Nucl. Fusion,* submitted).

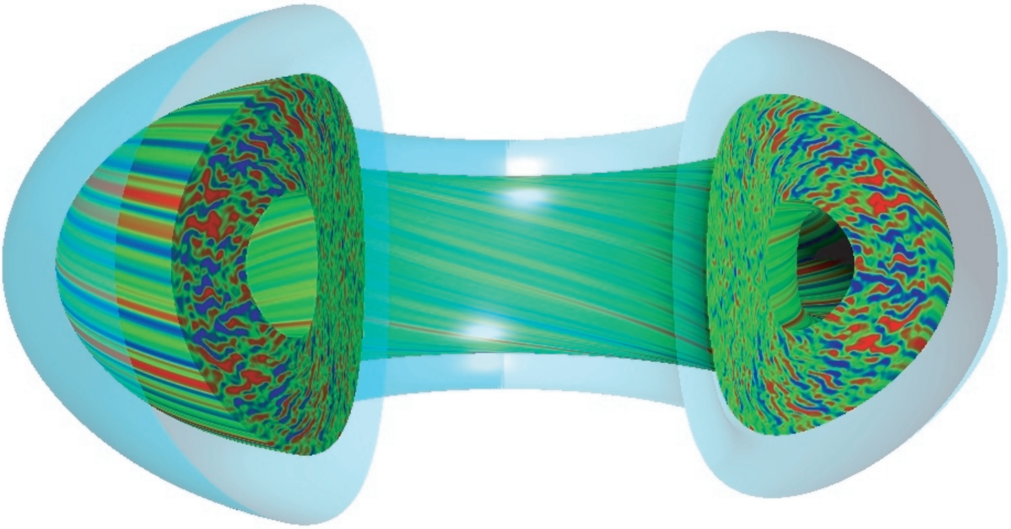

FIGURE 3.2 Contours of constant potential from a computer simulation of plasma turbulence in the DIII-D tokamak using the GYRO code. Note that the turbulent eddies are elongated along the magnetic field, while shear in the plasma electric and magnetic field ($E \times B$) rotation prevents structures with a cross-field dimension greater than ~$10\sigma_i$ from forming. Courtesy of General Atomics.

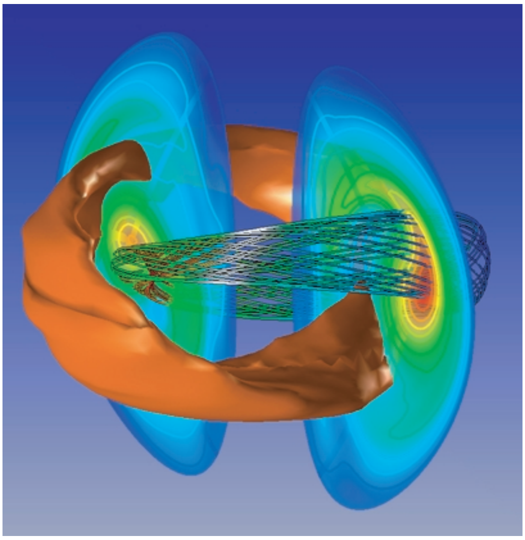

FIGURE 3.3 A spherical tokamak with a saturated magnetic island due to sheared toroidal rotation, as predicted by the M3D code. Courtesy of W. Park, Princeton Plasma Physics Laboratory.

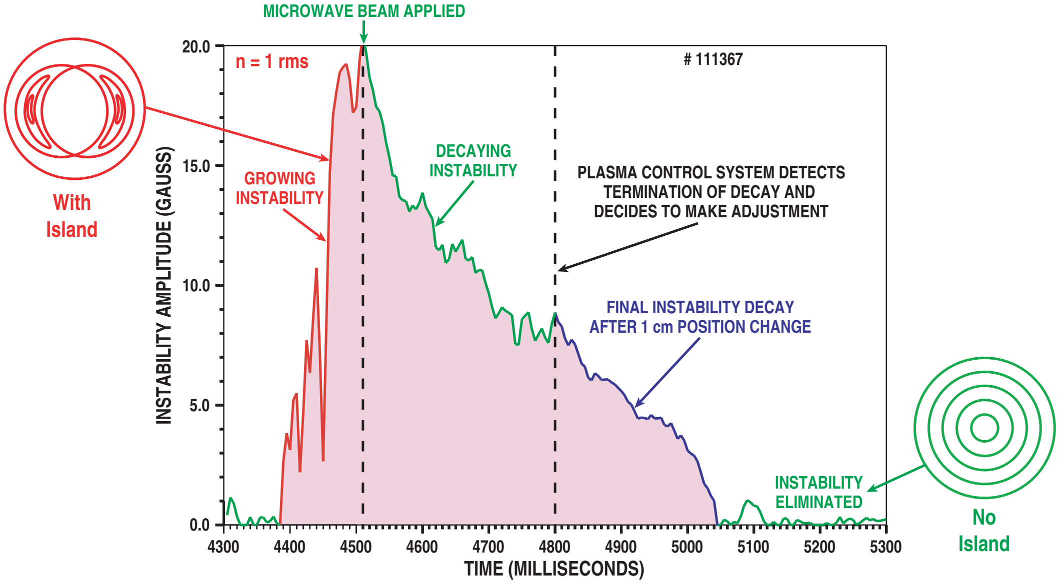

FIGURE 3.4 Time evolution of neoclassical tearing mode and response of the plasma control system. Applying and adjusting the precise position at which the microwave power is deposited stops the growth of a neoclassical tearing mode and then eliminates it. Courtesy of General Atomics.

this density limit. However, since fusion power gain generally increases with plasma density, developing a predictive understanding of this limit and methods to circumvent it could potentially yield great benefit.

> *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 with a burning plasma experiment.*

Mitigation of Abnormal Events

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 by operating below established stability limits. If excursions beyond these safe operating limits should occur, new techniques, such as the injection of argon gas, may be used to quench the plasma and avoid damage due to runaway electrons and reduce erosion due to high heat fluxes (see Figure 3.5). Model calculations indicate that this gas-injection technique will be applicable on the larger plasmas in ITER.[4] Research should continue to extend these results to larger plasmas and further validate the gas-penetration models. Further experiments are also needed to confirm that "thermal-quench" damage to the walls and/or divertor plates can simultaneously be avoided.

There is an instability near the plasma edge, the edge-localized mode (ELM), that can cause large and repetitive heat loads on plasma-facing components and, in turn, can severely limit component lifetimes. While a predictive understanding of these modes is still in development, experiments have now identified regimes with good plasma performance and with either significantly reduced or no edge-localized oscillations. These results provide some level of confidence that the deleterious effects of these ELMs can be avoided. However, further research and development are required, both to better understand these edge-localized modes and to develop reliable methods to mitigate peak heat loads without degrading burning plasma performance.

> *There must be sufficient confidence that disruptions and other abnormal events can be avoided or mitigated. While there is such confidence, further research and development are needed to develop plasma operating regimes that present less stringent heat loads to plasma-facing components.*

Maintenance of Plasma Purity

The introduction of impurities into the plasma, either as helium from fusion reactions or from sputtered first-wall materials, can significantly degrade plasma performance. Experiments have demonstrated that these impurities can be successfully removed from the plasma as neutral gas, formed when plasma recombines in the divertor. 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. Since most of these observations are empirical, further work on developing theoretical models of impurity and ash transport in the plasma core region is needed. This impurity-removal issue is especially important for advanced tokamak operating regimes in which the ion (and impurity) confinement in the plasma core is considerably improved.

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[4] D.G. Whyte, T.G. Jernigan, A. Humphreys, A.W. Hyatt, C.J. Lasnier, P.B. Parks, T.E. Evans, M.N. Rosenbluth, P.L. Taylor, A.G. Kellman, D.S. Gray, E.M. Hollmann, and S.K. Combs, "Mitigation of Tokamak Disruptions Using High-Pressure Gas Injection," *Phys. Rev. Lett.* **89,** 055001 (2002).

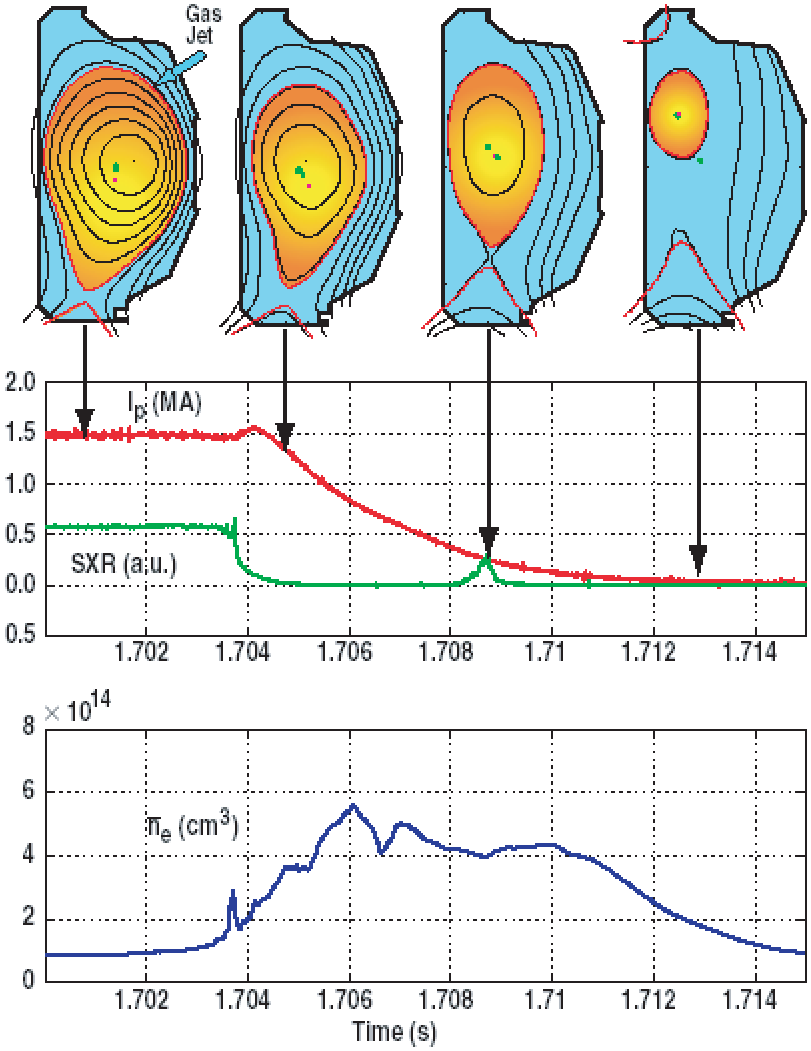

FIGURE 3.5 The controlled termination of a DIII-D tokamak discharge by injection of a noble gas. This technique holds great promise as a means of mitigating damage that might otherwise occur during an abnormal event in ITER. Courtesy of General Atomics.

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

Characterization Techniques

The scientific evaluation of a burning plasma experiment requires the reliable measurement of key quantities with good spatial and temporal resolution in a high-neutron environment. Important factors include adequate diagnostic access and the remote maintenance of measurement instruments. There is confidence that most of these measurements can be made with adequate precision, assuming appropriate flexibility in the design of the burning plasma 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.

Techniques must be, and are, available to adequately characterize and evaluate most of the important parameters in a burning plasma.

Plasma Control Techniques

ITER has both been designed to and is expected to achieve the key goal of studying the burning plasma regime in a conventional high-confinement (H-mode) regime. While many of the important scientific issues relating to burning plasmas can be addressed in this regime, the ability to operate in a high-performance regime—the so-called advanced tokamak regime—will be an important step on the path to an economically attractive fusion power plant.

Experiments in auxiliary-heated tokamaks have demonstrated that operational limits 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 presents additional challenges. The complexity arises from nonlinear interactions between the pressure profile, the heating source (proportional to the square of the plasma pressure), the self-driven currents (proportional to the pressure gradients), and 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, there is need for further research and development on fueling the central plasma (for pressure-profile control) and control of plasma rotation (for stabilization of resistive wall modes). Further research and development are required to develop methods to control plasma transport (including the control of internal transport barriers) and the interaction of radiofrequency heating sources with fusion alpha particles in the advanced tokamak regime. Research should also continue to develop techniques to stabilize resistive wall modes with feedback and to control both the electron density and electron-density profile.

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

Conclusion

In the past several years, significant progress has been made in the understanding and control of fusion plasmas through advances in a broad range of critical scientific issues. Small, focused experiments have led to critical understanding of issues such as the self-driven bootstrap currents necessary to efficiently sustain fusion-grade tokamak plasmas. Larger-scale facilities are also successfully developing key concepts for more attractive fusion energy concepts and for the control of fusion plasmas. All of these scientific developments positively impact the potential for developing an attractive fusion concept, as well as increasing our fundamental understanding of the plasma state of matter. This type of progress in fusion science and fusion technology has led to confidence that the global fusion community is scientifically ready to take the burning plasma step.

TECHNICAL READINESS

The need to assess the technical readiness for an experiment such as ITER is as important as understanding the scientific readiness to undertake a burning plasma experiment. In this section, the following six criteria that define technical readiness to create and study burning plasmas are considered:

1. Fabrication of necessary components,
2. Component lifetime in a nuclear environment,
3. Lifetime of plasma-facing components,
4. Tritium inventory control,
5. Remote maintenance, and
6. Fueling, heating, and current drive control.

Fabrication of Necessary Components

The required techniques for fabricating components for ITER have been successfully demonstrated with prototypes (see Figures 3.6 and 3.7). Successful prototype components[5] have been built for all major systems, including full-scale vacuum-vessel sectors.[6,7] The magnet coil designs have been verified to meet the field requirements with a good engineering safety margin.[8] Scenarios for remote fabrication and repair have also been tested.

> *The necessary components for ITER can be manufactured and assembled, including the required magnetic field coils, the vacuum vessel, divertor, and first-wall components.*

Component Lifetime in a Nuclear Environment

The lifetime of the various parts of a working fusion reactor must be shortened as little as possible by damage from operating in a nuclear environment. The design of a burning plasma device must include adequate shielding for the magnetic field coils; thus, research is continuing to improve the radiation resistance of electrical insulators to permit increased mission life. This effort will be particularly important for insulators in copper-coil designs in order to optimize the number of full-power discharges.[9] Further research and development are needed for diagnostics, including those sited in high-neutron-flux areas and those requiring transparent optical materials. Further research is required to develop beam-based fluctuation diagnostics for a burning plasma experiment.

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[5] R. Aymar, "ITER R&D: Executive Summary: Design Overview," *Fusion. Eng. Des.* **55**, 107-118 (2001).

[6] K. Ioki, V. Barabash, A. Cardella, F. Elio, G. Kalinin, N. Miki, M. Onozuka, T. Osaki, G. Sannazzaro, Y. Utin, M. Yamada, and H. Yoshimura, "Design and Fabrication Methods of FW/Blanket and Vessel for ITER-FEAT," *Fusion Eng. Des.* **58-59**, 573-578 (2001).

[7] K. Ioki, P. Barabaschi, V. Barabash, S. Chiocchio, W. Daenner, F. Elio, M. Enoeda, A. Gervash, C. Ibbott, L. Jones, V. Krylov, T. Kuroda, P. Lorenzetto, E. Martin, I. Mazul, M. Merola, M. Nakahira, V. Rozov, Y. Strebkov, S. Suzuki, V. Tanchuk, R. Tivey, Y. Utin, and M. Yamada, "Design Improvements and R&D Achievements for Vacuum Vessel and In-Vessel Components Towards ITER Construction," *Nucl. Fusion* **43**, 268-273 (2003).

[8] H. Tsuji, S. Egorov, J. Minervini, N. Martovetsky, K. Okuno, Y. Takahashi, and R. Thome, "ITER R&D: Magnets: Central Solenoid Model Coil," *Fusion Eng. Des.* **55**, 153-170 (2001).

[9] The committee notes that although ITER is at present designed with Nb_3Sn coils, existing machines and planned alternative confinement devices make use of copper-coil technology.

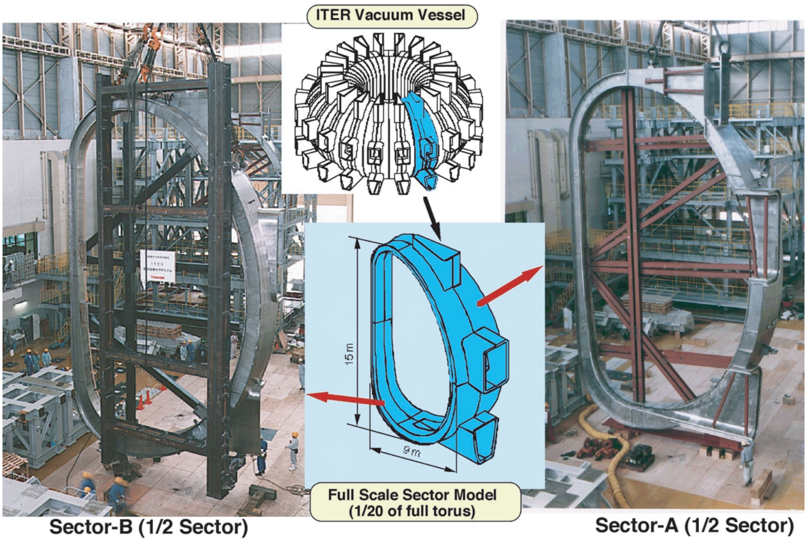

FIGURE 3.6 Full-scale prototype of an ITER vacuum-vessel sector, constructed in Japan. Courtesy of ITER.

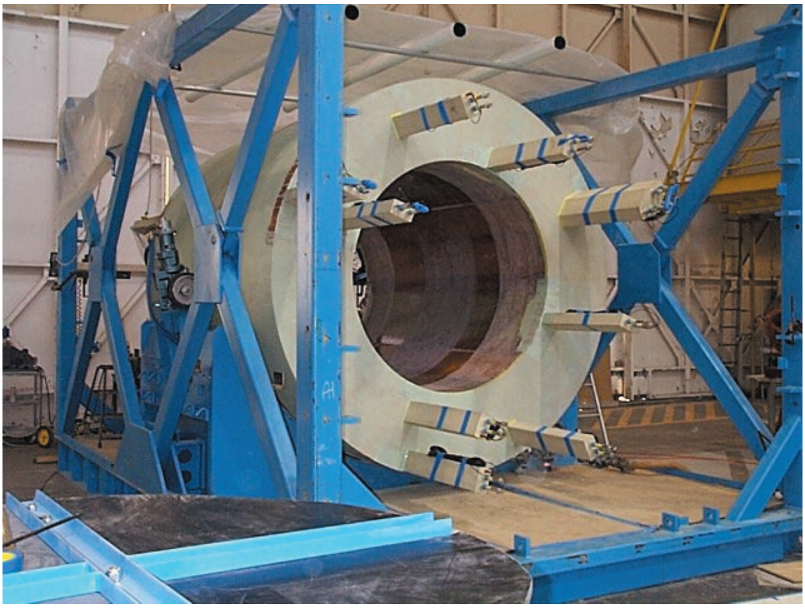

FIGURE 3.7 ITER central solenoid model coil that achieved 13 T. Courtesy of ITER.

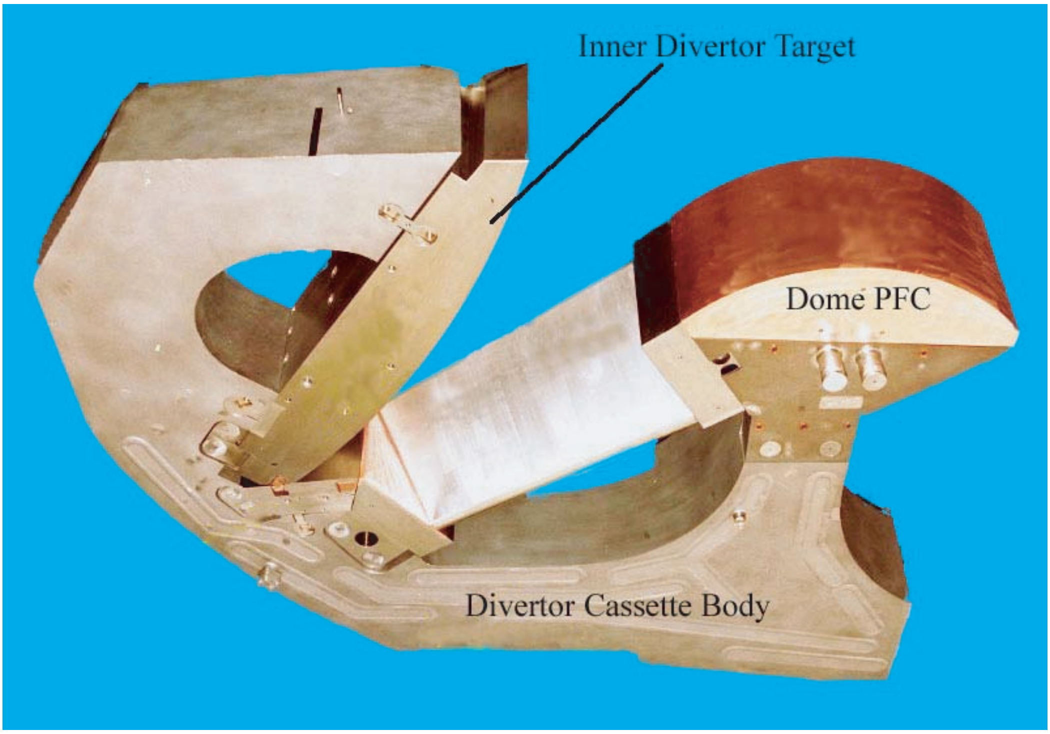

FIGURE 3.8 Prototype of a divertor plasma-facing component (PFC) for ITER. Courtesy of ITER.

There is sufficient assurance that major components can survive in the required nuclear environments.

Lifetime of Plasma-Facing Components

Prototype designs of plasma-facing components (see Figure 3.8) have been tested for normal heat-flux conditions, and it has been demonstrated that the mechanical designs can accommodate the projected disruption forces.[10] Both carbon-based materials and refractory metals (e.g., tungsten and molybdenum) have

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[10] K. Ioki, V. Barabash, A. Cardella, F. Elio, Y. Gohar, G. Janeschitz, G. Johnson, G. Kalinin, D. Lousteau, M. Onozuka, R. Parker, G. Sannazzaro, and R. Tivey, "Design and Material Selection for ITER First Wall/Blanket, Divertor and Vacuum Vessel," *J. Nucl. Mater.* **258-263**, 74-84 (1998).

been qualified for fusion devices. Techniques have been developed to mitigate the heat loads expected from plasma disruptions in order to ensure component integrity and sufficient erosion lifetimes. The one exception is the case of edge-localized modes typical of the highest-performance plasmas. These instabilities can cause rapid and repetitive deposition of energy to the plasma-facing components. The resulting erosion greatly shortens component lifetimes. Experiments have shown that some mitigation is possible by plasma shaping and edge density control with little loss of confinement. Further research on the mitigation of these edge instabilities is required.

> *Plasma-facing components can be designed and built to handle the anticipated heat flux, particle flux, and mechanical stresses necessary for use in a burning plasma experiment, including those experienced during most disruptive discharge terminations.*

Tritium Inventory Control

Safety analyses have found that all of the proposed burning plasma devices meet fusion safety standards, and none of the devices requires an evacuation plan beyond the site boundary. There are proven techniques[11] for separating hydrogen isotopes, cleaning up tritium gas, and delivering deuterium and tritium to the plasma. In the case of ITER, the throughput, tritium inventory, and processing rate must all be increased by a factor of 10 to meet the design specifications. In addition, experiments have shown that eroded and redeposited material from carbon components (currently the material of choice for plasma-facing components) traps unacceptably large amounts of tritium. In this key area, further research will be required.

> *The required tritium inventory can be handled safely, but further research is required to develop plasma-facing components that can reduce the tritium inventory.*

Remote Maintenance

Successful remote handling of in-vessel components has been accomplished on the Joint European Torus. Full-size prototypes of major remote handling systems for a burning plasma experiment have been designed and tested. Optimization of the designs for specific burning plasma devices is continuing.

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[11] H. Yoshida, D. Murdoch, M. Nishi, V. Tebus, and S. Willms, "ITER R&D: Auxiliary Systems: Tritium Systems," *Fusion Eng. Des.* **55**, 313-323 (2001).

The remote maintenance required to operate a burning plasma experiment can be accomplished.

Fueling, Heating, and Current Drive Control

The injection of frozen pellets of deuterium-tritium is a proven method for fueling fusion plasmas. The use of ion cyclotron heating, electron cyclotron heating and profile control, and lower hybrid heating and current drive are well established. Techniques to use high-energy, negative-ion, neutral-beam heating to heat fusion plasmas have been developed in Japan. Various plasma heating and current drive systems require antennas, waveguides, and mirrors near the plasma (see Figure 3.9 for performance of one example). The choice of structural materials, insulators, and guard materials for these structures is still being optimized.

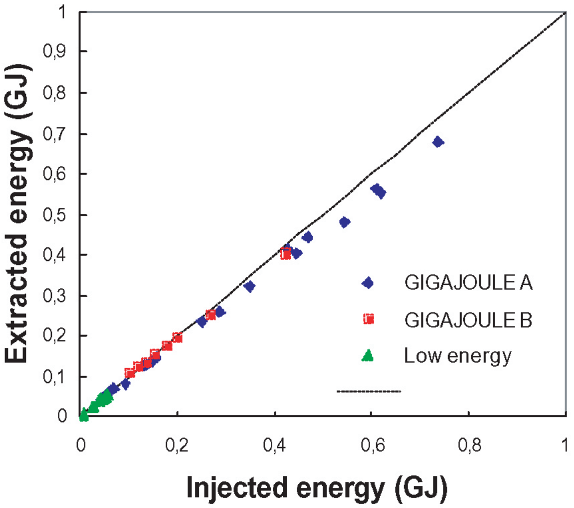

FIGURE 3.9 Results of experiments using an actively cooled limiter on the Tore Supra tokamak in Cadarache, France. Calorimetry has proven to be a valuable tool to confirm injected energy values, as all actively cooled components are equipped with temperature sensors. The balance between injected and extracted energy presented here shows excellent agreement: More than 95 percent of the injected energy is recovered. SOURCE: J. Jacquinot, in "Recent Developments Towards Steady State Physics and Technology of Tokamaks in Cadarache," *Proceedings of the 19th International Atomic Energy Agency Fusion Energy Conference,* Lyon, France, October 2002; forthcoming in *Nuclear Fusion,* Winter 2003. Courtesy of J. Jacquinot, Euratom-Commissariat à l'Énergie Atomique (CEA), CEA Cadarache; Tore Supra, France; and International Atomic Energy Agency.

Adequate fueling, heating, and current drive techniques have been developed to control and evaluate burning plasmas.

Conclusion

The committee finds that the six technical criteria discussed above have now been satisfied, except for a few remaining areas (described in Chapter 4—see the subsection entitled "Directly Support the Burning Plasma Program on ITER"), in which ongoing research is expected to adequately address these outstanding issues.

Significant progress has been made in the development of the technology needed to implement a fusion machine of the scale and nature of ITER. It is clear that ongoing research can be expected to adequately address technical issues requiring continued attention, but no issues remain that would undermine the fusion community's assertion that it is technically ready to undertake a burning plasma experiment. 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 from the ITER program in 1998.

4

Program Structure and Balance

INTRODUCTION

From the discussions in this committee's interim report (see Appendix E) and from the expanded analysis in the previous chapters, it is clear what can be learned from a burning plasma experiment and why the overall understanding achieved in the past decade makes a burning plasma experiment possible. On the basis of these considerations, and given the centrality of a burning plasma experiment to the development of fusion energy, the committee affirmed in December 2002 in its interim report and reaffirms here its recommendation that the U.S. fusion program participate in a burning plasma experiment. The committee also concludes that the best opportunity for the United States to pursue a burning plasma experiment is through participation in the International Thermonuclear Experimental Reactor (ITER) project. Subsequent to the issuance of the committee's interim report, the U.S. government announced its decision to enter negotiations to participate in the ITER experiment. The U.S. and world fusion communities are already acting on this decision, and negotiations are in progress to define the possible roles of all potential participants in the ITER program.

The discussion in this report has concentrated on issues directly related to participating in a burning plasma experiment. The previous two chapters focused on addressing the first two elements of the committee's charge by discussing in detail the scientific and technical importance of a burning plasma experiment and the overall readiness of the fusion community to enter into such an experiment. This chapter addresses issues arising from the third element of the charge, which asks for "an independent review and assessment of the plan for the U.S. magnetic fusion burning plasma experimental program. . . [and] recommendations on the program strategy aimed at maximizing the yield of scientific and technical understanding as the foundation for the future development of fusion as an energy source" (see Appendix A). The committee notes that apart from being presented with some short-term budget plans from the Office of Fusion Energy Sciences (OFES), progress reports on the state of the ITER negotiations, briefings on the activities and reports of the Fusion Energy Sciences Advisory Committee (FESAC), and reports on the status of the various elements of the current research program, the Burning Plasma Assessment Committee was not presented with a coherent and singular strategy for the OFES program. The committee strives to present a foundation for such a strategy in this report, as detailed in this chapter. It should be noted that because the committee's charge was limited to the consideration of magnetically confined burning plasmas, none of the inertial confinement fusion programs is considered here.

Since the decision to reenter the negotiations on participation in ITER has been made by the U.S. government, it is necessary to consider the context and impact of this decision on the U.S. fusion program. The pursuit of a burning plasma experiment is a large undertaking that will necessarily require a significant shift in the distribution of activities in the U.S. fusion program. Even on a success-oriented schedule, experiments on ITER will not begin for approximately 10 years, and they will run for a decade or more. The Department of Energy's fusion program must be designed both recognizing this timescale and addressing the importance of balancing the pursuit of the other critical issues of fusion science needed to establish the basis for fusion energy.

In its interim report, the committee listed some minimal level of participation in the ITER program to which the U.S. fusion program should commit in order to gain sufficient benefit from this opportunity to study burning plasmas. It said, "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" (see Appendix E, p. 157).[1] The committee reaffirms this conclusion.

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[1] The committee notes that the text in the interim report has a comma between the words "facility" and "consistent" in this quotation. Since publication of that report, the committee has become aware of the potential for the original formulation being interpreted in a manner inconsistent with the committee's intent. Therefore, as shown in the Summary of the present report and in the list of recommendations later in this chapter, the committee has removed that comma. The removal of the comma reasserts the committee's intended meaning, namely, that the U.S. role in producing the high-technology components of the facility be consistent with the size of the U.S. contribution.

With at least that level of participation in mind, the following question arises: What general areas of domestic research activity are required in anticipation and support of, and as a complement to, burning plasma experiments in ITER?

To consider and answer this question in the interest of maximizing the scientific yield of the entire U.S. fusion science program, including a burning plasma experiment, the committee presents in this chapter a discussion of the domestic fusion science research program. The outstanding compelling scientific issues facing the program are considered in the following major section, entitled "Fusion Science Issues and Research Portfolio," and how elements of the program will address these issues is discussed in the section after that, "Research Opportunities and Science and Technology Goals for the Domestic Fusion Program."

Developing any energy source is a long and difficult task. Typically, the time from concept to facility is more than three decades after the basic concept has been proven. Fusion has not reached the stage for building a successful demonstration reactor and is thus relatively immature as an energy source. The ultimate success of producing an economically attractive new energy source is far in the future, and many outstanding scientific and technical issues have to be resolved before the path forward is well defined. Recognizing this, the 2001 study by the National Research Council's Fusion Science Assessment Committee (FUSAC) recommended that the U.S. fusion program focus on addressing the compelling scientific issues and thereby strengthen the underlying science base of a fusion energy source.[2] The committee agrees with this approach.

This chapter focuses on the following issues: the critical science issues to be confronted by the U.S. fusion science program; research activities that could be undertaken over the next several years to prepare for experiments on ITER; fusion science issues to be addressed in a portfolio of smaller-scale research programs and specific goals to be pursued in those programs; the need for continuing efforts in theory and simulation; and concerns regarding education and workforce development relevant to achieving this overall program. The last two major sections of the chapter discuss the need for changing the structure of and setting priorities for the U.S. fusion program in the context of a decision to proceed with a burning plasma experiment.

In formulating the rationale behind its recommendations, the committee focuses its discussion on research elements that will be important in the next few years and provides general guidance for the rest of the decade. The details for later

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[2] National Research Council, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, Fusion Science Assessment Committee (FUSAC), Washington, D.C.: National Academy Press, 2001 (referred to as NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*), p. 3.

years are necessarily more general, because the understanding of phenomena such as turbulence, transport, and stability will deepen through theory, simulation, and experiments on existing and planned facilities. These advances are likely to change the course of the ITER program and other experiments in significant ways. Plans will evolve as understanding grows—as new ideas and priorities for the experimental plan itself are put forward, as new ways of interpreting experiments (and the tools to do this) are developed, and as confidence grows about the extrapolation of results.

FUSION SCIENCE ISSUES AND RESEARCH PORTFOLIO

As discussed earlier, the mission of the U.S. fusion science program is to advance "the knowledge base needed for an economically and environmentally attractive fusion energy source."[3] As noted in the goals of the U.S. fusion program, this requires advances in the fusion science of plasma confinement and fusion technology. For magnetic confinement, the key overarching goals for achieving attractive fusion energy are these:

- Maximize the plasma pressure,
- Maximize the plasma energy confinement,
- Minimize the power needed to sustain the plasma configuration, and
- Simplify and increase reliability of the overall system.

The first three of these goals directly address increasing the economic appeal of fusion energy by increasing the efficiency of utilizing the magnetic field, increasing the power density, and decreasing the recirculating power. The fourth goal relates to overall system attractiveness and feasibility. The tokamak configuration of magnetic fields has made the greatest progress in advancing these goals and is thus capable of exploring burning plasmas. A burning plasma experiment would enable a large step forward by confronting these goals in a strongly fusing environment for the first time.

As discussed in Chapter 2, there is a highly nonlinear interaction between the plasma and the magnetic field during plasma confinement. As a consequence, there are many arrangements of the magnetic field that confine plasma and offer possible advantages on these goals over the conventional tokamak. The various

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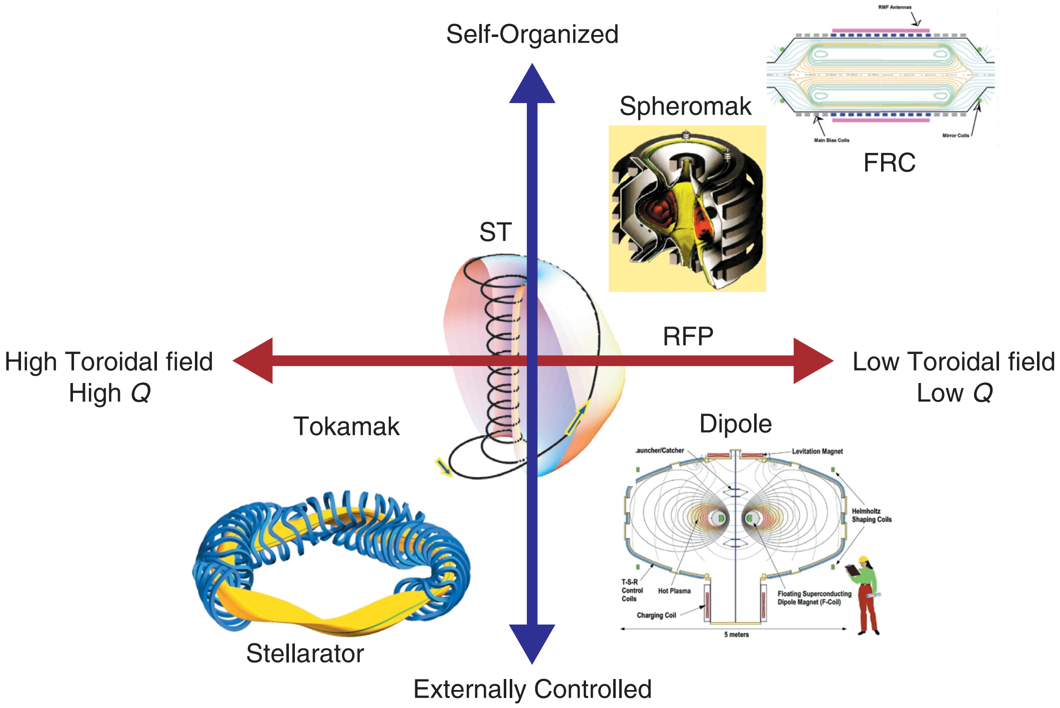
[3] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

configurations differ primarily by the degree to which the magnetic field is controlled externally or is self-organized by the plasma and plasma currents (see Figure 4.1 and the sidebar entitled "Magnetic Fusion Research Configurations").

The U.S. fusion program is focused on innovation and concept optimization, based on developing predictive understanding of the underlying physics. Accomplishing the program goals requires the investigation of the following issues:

- Plasma turbulence and turbulent transport,
- Stability limits to plasma pressure,
- Stochastic magnetic fields and self-organized systems,
- Plasma confinement with different types of magnetic field symmetry,
- Control of sustained high-pressure plasmas,
- Energetic particles in plasmas, and
- Plasma behavior when self-sustained by fusion (burning).

A burning plasma experiment is a crucial step for the development of fusion science and technology. It will offer exciting opportunities to study the burning plasma physics issues, as discussed in Chapter 2. It is appropriate to ask what other



MAGNETIC FUSION RESEARCH CONFIGURATIONS

The main experimental configurations for magnetic fusion research can be usefully listed in order of the increasing fraction of magnetic field from external coils or, equivalently, in order of the decreasing degree of self-organization of the plasma configuration (see Figure 4.1). They include the field-reversed configuration (FRC), the spheromak, and the reversed-field pinch (RFP), all of which explore low-magnetic-field plasma configurations that rely on strong self-organization of plasma currents. These devices potentially offer more compact and more efficient confinement configurations but face formidable issues of plasma stability and sustainability.

As the fraction of externally imposed magnetic field is increased, improved plasma stability and confinement are obtained, and fusion-grade plasma conditions are accessible. The devices that operate in this way range from the spherical torus (ST) to the tokamak and advanced tokamak, and, finally, the stellarator. The ST and advanced tokamak experiments use geometrical variations and increasingly sophisticated active control tools to optimize the performance and confinement efficiency of the plasma. These two types of devices are stabilized by relatively strong external magnetic fields, but also include significant plasma current and some self-organizing features of plasma behavior. The stellarator uses magnetic fields almost completely generated by external coils and, through three-dimensional shaping of the configuration, provides stable steady-state operation in the fusion regime without requiring plasma currents.

The dipole configuration uses a relatively small superconducting ring floating within a large vacuum chamber to confine a hot plasma. It has the possibility of being steady state with classical confinement and high beta. Compared with a tokamak, the dipole configuration would not require current drive; however, the internal floating ring provides a technical challenge.

More details on these confinement configurations are presented in Appendix F, "Fusion Reactor Concepts."

FIGURE 4.1 Comparison of the main experimental configurations for magnetic fusion research. The various configurations are displayed relative to their level of self-organization and the strength of their toroidal magnetic field. NOTE: ST—spherical torus; RFP—reversed-field pinch; FRC—field-reversed configuration; *Q*—fusion gain factor. Individual images courtesy of the Max-Planck-Institut fuer Plasmaphysik; M. Peng, Oak Ridge National Laboratory; Lawrence Livermore National Laboratory; A. Hoffman, University of Washington, Redmont Plasma Physics Laboratory; M. Mauel, Columbia University.

activities are needed in order to investigate and resolve the full range of issues in fusion science. In order to maximize progress toward the goal of developing an attractive fusion energy source, how should the program be balanced between a program of burning plasma studies and a program of non-burning-plasma studies addressing other critical issues of fusion science and basic plasma physics?

The proposed burning plasma experiment (ITER) is a tokamak; its design uses the best current understanding of accessible confinement. The committee concludes, in its interim report and in this report, that the fusion community is ready to take the step of proceeding with a burning plasma experiment. However, ITER is not a demonstration fusion reactor; significant further improvements will be required in order to develop an attractive fusion system—these improvements would need to include increasing plasma pressure, efficient stable sustainment to steady state, and higher generated fusion power density. The magnitude of the improvements needed can be estimated by comparing the ITER design with the Advanced Reactor Innovation Evaluation Study (ARIES) designs for projected attractive fusion energy systems.[4] The ARIES studies generally assume that significant progress on each of the issues mentioned above achieves higher performance than has been demonstrated experimentally. These studies provide targets for the development of fusion energy systems and the associated fusion science experimental program.

Table 4.1 compares the characteristics of ITER and the ARIES-RS (Reverse Shear) and ARIES-AT (Advanced Tokamak) studies, in which the normalized pressure is the ratio of the average plasma pressure to the vacuum magnetic pressure at the horizontal midpoint of the plasma. The ARIES designs project to economically attractive performance by producing 4 to 5 times more fusion power in less than half the plasma volume of ITER. They assume that the normalized pressure can be increased by a factor of 2 to 3 and that the plasma current can be sustained almost entirely by the pressure-generated bootstrap current, increasing the power gain (Q) of the reactor. One focus of the ongoing program is to achieve this level of plasma performance.

The U.S. fusion program today is pursuing several research avenues to develop an understanding of the outstanding and compelling scientific issues, pursue the goals of the program, and thereby achieve such improvements. Some efforts—referred to as advanced tokamak research—involve modifications to the tokamak, leading to improved steady state. In addition, the current program includes re-

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[4] The ARIES program is a national, multi-institutional research activity for performing advanced integrated design studies of the long-term fusion energy embodiments to identify key research and development directions and to provide visions for the fusion science program. This research is funded by the DOE Office of Fusion Energy Sciences.

TABLE 4.1 Comparison of the Characteristics of the International Thermonuclear Experimental Reactor (ITER) and Two Advanced Reactor Innovation Evaluation Studies (ARIES)—Reverse Shear (ARIES-RS) and Advanced Tokamak (ARIES-AT)

Parameter	ITER[a] Pulsed	ITER[a] Steady State	ARIES-RS[b]	ARIES-AT[c]
Radius (m)	6.2	6.4	5.5	5.4
Plasma volume (m^3)	831	770	351	329
Normalized pressure (percent)	2.8	2.8	5	9.2
Normalized confinement ($H_{98y,2}$)	1.0	1.6	1.5	1.8
Pressure-driven current fraction (percent)	Not available	48	88	91
Magnetic field strength (T)	5.3	5.2	8.0	5.6
Fusion power (GW)	0.5	0.36	2.17	1.76
Q (fusion power/power supplied)	10	6	22	49

NOTE: The normalized pressure is the ratio of the average plasma pressure to the vacuum magnetic pressure at the horizontal midpoint of the plasma.

[a] From "ITER Technical Basis," available online at http://www.iter.org/ITERPublic/ITER/PDD4.pdf. Accessed June 1, 2003.

[b] From "Overview of the ARIES-RS (Reverse Shear) Tokamak Fusion Power Plant," available online at http://aries.ucsd.edu/LIB/REPORT/CONF/ISFNT4/najmabadi.pdf and http://aries.ucsd.edu/ARIES/DOCS/ARIES-RS/RS6/output.html. Accessed June 1, 2003.

[c] From "ARIES-AT: An Advanced Tokamak, Advanced Technology Fusion Power Plant," available online at http://aries.ucsd.edu/LIB/REPORT/CONF/IAEA00/najmabadi.pdf and http://aries.ucsd.edu/miller/AT/output.html. Accessed June 1, 2003.

search on innovative magnetic configurations that change the interaction of the plasma with the magnetic field. These concepts have developed and tested our understanding of improving fusion performance.

There are many elements to consider when addressing how the current portfolio of research activities in the OFES program should evolve as the nation undertakes to participate in a burning plasma experiment at the same time that compelling scientific issues remain to be addressed. In the following pages, these scientific issues are considered in more detail. The discussion here focuses on the importance of these issues to the progress of the understanding of fusion science from the perspective of a non-burning-plasma program. How a burning plasma experiment, such as ITER, might address some of these questions was discussed in Chapter 2 (see the section entitled "Scientific Importance of a Burning Plasma for Fusion Energy Science and the Development of Fusion Energy," p. 54).

Plasma Turbulence and Turbulent Transport

A key to high fusion performance in burning plasmas is the suppression of turbulence and the transport of pressure and particles that it generates. Over the past two decades, a number of methods to suppress ion turbulence have been discovered, including stabilization by sheared flows. In addition, there has been recognition that sheared flows can be generated by the turbulence, establishing its saturated amplitude and transport level. Experiments directly testing the theoretical understanding of turbulence suppression are in progress on fusion experiments and smaller basic laboratory experiments. These experiments, together with continued progress in theory and simulation, will lead to improved predictive understanding. In particular, there is an acute need for improved understanding of electron turbulence and its effect on transport, as well as of edge transport and its influence on energy.

Building on improved understanding, new magnetic configurations have been designed to facilitate the suppression of ion turbulence. In the advanced tokamak and stellarator, "reversed" or weak shear of the magnetic field's helical twist weakens the turbulence drive, lowering the threshold for suppression. Turbulence suppression has been observed in such advanced tokamak experiments and is generally consistent with theoretical simulations. The spherical torus is predicted to have large-enough pressure-driven flow shear to suppress ion turbulence directly. This is being tested in ongoing experiments. Further improvements in the understanding of plasma turbulence will enable better configuration designs.

Stability Limits to Plasma Pressure

Increasing the plasma pressure that can be confined stably is key to developing more attractive fusion energy. Consequently, all of the research on magnetic configurations seeks to increase the maximum stable pressure limit. The experimentally observed stability limit in tokamaks is in reasonable agreement with theoretical predictions. Methods to increase the stability limit have been developed and incorporated in the advanced tokamak configurations—these methods include the use of a highly elongated and triangular plasma shape, modifications of the plasma current or magnetic shear profiles, and the stabilization of pressure-limiting instabilities using active feedback or close-fitting conducting structures.

The spherical torus configuration was designed, building on the understanding of tokamak stability, to have a very high normalized pressure limit. This increased limit has been demonstrated experimentally and is a significant motivation for investigating spherical torus plasmas for fusion energy.

Stability pressure limits in stellarators and in reversed-field pinch (RFP) have not been experimentally observed. Experiments are under way to search for these limits and to compare theoretical predictions with observed behavior. In stellarators, however, the achieved pressures already significantly exceed theoretically predicted instability thresholds, and improved nonlinear models are being investigated. New experiments, designed using current understanding, will explore the theory at higher pressure levels and will evaluate access to normalized pressures more attractive in terms of stability. The experimentally observed normalized pressure in RFPs is already high enough (approximately 10 percent) to motivate investigation of that configuration.

Stochastic Magnetic Fields and Self-Organized Systems

In configurations in which plasma currents dominantly produce the magnetic field, or in which the plasma is unstable owing to tearing (or reconnection) instabilities, the magnetic field can become stochastic or turbulent. In this case, the motion of the plasma along these magnetic field lines can lead to a loss of particles and energy. Such systems can also self-organize, owing to nonlinearities in the plasma dynamics, as is observed in the RFP. An experimental understanding of the magnetic turbulence observed in RFPs has been used to develop methods to suppress the turbulence, improving the plasma confinement. The basic method is to carefully adjust the current profile near the plasma edge using external current drive. This method reduces the free energy driving the instabilities and is calculated to return the magnetic field to a nonturbulent state.

The magnetic topology can also change as a result of local magnetic reconnection. This phenomenon is being investigated in several research groups in a concerted attempt to understand the fundamental mechanisms of the process. A number of experiments to investigate magnetic reconnection have clarified, although not yet completely illuminated, the physical mechanisms. Detailed measurements of the reconnection process have been performed. The magnetic structure of the region where the field lines break and reconnect is observed to be flattened, so the reconnection flows are not fast. Inside this region turbulence accelerates the reconnection process. The generation of this turbulence and the effect on the rate of reconnection are now partially understood. The experimental effort is complemented by a large coordinated effort to simulate reconnection using high-performance computing and supporting theoretical analysis. The computations have revealed the role of turbulence within the reconnection region. The combined experiment, theory, and simulation program has not reached the point at which the rate of reconnection can be reliably predicted. However, progress is rapid, and the results are already changing the interpretation of reconnection events in fusion experiments.

Plasma Confinement with Different Types of Magnetic Field Symmetry

In tokamaks and most of the other magnetic configurations, the magnetic field does not vary in the toroidal direction and thus is toroidally symmetric. This symmetry is important, as it ensures confinement of plasma-particle orbits and low damping of the plasma flow in the toroidal direction. Theoretical studies in the 1980s demonstrated that good particle orbit confinement could be achieved in three-dimensional stellarator magnetic configurations by making the magnitude of the magnetic field strength be constant along a specified direction in a suitable flux coordinate system. These configurations are called quasi-symmetric. The quasi-symmetry can be chosen to be in a toroidal, helical, or poloidal direction. Such configurations have low flow-damping in the quasi-symmetric direction and can be designed to have orbit confinements as good as or better than a similar tokamak. Recently, the first quasi-symmetric (helical) experiment began operation. It has already observed signatures of confinement improvement with quasi-symmetric magnetic fields.

New stellarator experiments are under construction to test quasi-toroidal and quasi-poloidal symmetry. They are designed to have excellent orbit confinement, while also optimizing the magnetic field distribution to increase the stability pressure limit. These experiments will determine whether three-dimensional magnetic field configurations can produce economically attractive fusion systems.

Control of Sustained High-Pressure Plasmas

Steady-state operation greatly increases the economic appeal of fusion systems. Efficiently sustaining and controlling high-pressure plasmas therefore constitute a critical issue. Toroidally symmetric configurations—including the tokamak, spherical torus, and reversed-field pinch—create part or most of the magnetic field using plasma current. This current must be generated either by the plasma pressure (the bootstrap current for the tokamak and spherical torus) or driven externally. Externally driven plasma current requires the injection of energy, which decreases the power gain of a fusion system. Thus, the advanced tokamak and spherical torus attempt to minimize the external current drive requirements by maximizing the pressure-driven bootstrap current. However, the profile of the pressure and current within the plasma must also be controlled to obtain stability for high plasma pressure. Feedback stabilization techniques may also contribute to controlling these high-pressure plasmas. These are significant areas of current research. While theoretically optimized solutions have been found, experiments have not yet observed steady-state-compatible high-pressure plasmas consistent with low amounts of external current drive. These investigations are crucial for establishing the benefits of the advanced tokamak and spherical torus configurations.

Taking a different approach, stellarators produce the magnetic field completely or dominantly by external coils (with the remnant due to the bootstrap current). Stellarators are compatible with steady-state operation and robust, as the magnetic configuration is maintained as long as the coils are energized. Theoretically, the pressure limit in stellarators can be relatively insensitive to the detailed profiles of pressure and the bootstrap current. This compatibility with steady state is a significant motivation for investigating stellarator plasmas for fusion energy.

Energetic Particles in Plasmas

A number of experiments have investigated how energetic particles—often beams of particles—excite waves and instabilities in plasmas. For example, the excitation of plasma waves, lower hybrid waves, and whistler waves by beams has been studied extensively. The theory of nonlinear wave–particle interaction has advanced considerably in the past 20 years and has been extensively validated against experiments. In burning plasmas, the excitation of Alfvén waves by the energetic fusion alpha particles is of significant concern. Different magnetic configurations can be more or less stable to these waves, offering opportunities for improvement. An outstanding issue is that of exploring the properties of these waves in the different configurations and developing a predictive understanding to guide the design of fusion configurations beyond any initial burning plasma experiment.

Plasma Behavior When Self-Sustained by Fusion

In a burning plasma, the dominant heat source arises from the fusion-produced fast alpha particles. This is fundamentally a nonlinear process, which will combine with the turbulent transport processes to modify the plasma equilibrium and stability properties. In addition, the fast alpha particles can directly generate fluctuations in the plasma and thereby influence the confinement of the alpha particles and possibly the background thermal plasma itself. The net result is a highly nonlinear plasma regime with strong elements of self-organization. Plasma regimes with the relevant population of fast alpha particles in a reactor-relevant size of experiment are accessible only in the proposed burning plasma experiments.

RESEARCH OPPORTUNITIES AND SCIENCE AND TECHNOLOGY GOALS FOR THE DOMESTIC FUSION PROGRAM

In considering the scale of effort needed to achieve a strategically balanced fusion science program and motivate its support, it is useful to identify specific goals to be addressed and activities to be pursued. The previous section considered the nonburning fusion program from the perspective of compelling scientific issues that must be addressed to make progress on the fusion program goals. In this section, the committee considers how the fusion goals can be addressed from a programmatic perspective. The questions addressed include these: What are the needs of the burning plasma program on ITER? What are the goals of the concept-optimization programs? What role is there for novel concepts? and What is the importance of developing fusion technologies? To address such questions, a range of opportunities for fusion science research over the next decade or so is presented.

This report is not the first effort to identify the opportunities for the U.S. fusion program as it prepares to incorporate a burning plasma experiment. The recent DOE Integrated Program Planning Activity[5] and the Snowmass studies by the fusion community itself[6] have described challenges and research opportunities for nonburning plasma fusion science. The DOE Integrated Program Planning Activity plan for the fusion program is organized around a detailed set of scientific issues and objectives. Together, the discussions that led to these reports established a range of science and technology goals for the fusion science program for the next 5 to 15 years.

From an examination of the studies referred to above, the NRC FUSAC review,[7] other community reviews, and presentations to this committee, the committee identified key areas in which ongoing U.S. research and development (R&D) are recommended for the domestic fusion science program. It should be noted that this list is strictly representative and not meant to be exhaustive. The actual choice of which opportunities to pursue must be determined through the usual federal government process, advised by the fusion community (as described later

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[5] *Integrated Program Planning Activity for the DOE's Fusion Energy Sciences Program*, December 2000; available online at http://vlt.ucsd.edu/IPPAFinalDec00.pdf. Accessed May 1, 2003. This plan established objectives at 5-year intervals, with detailed objectives for 2005, and envisioned a review at approximately that time.

[6] R. Bangerter, G. Navratil, and N. Sauthoff, *2002 Fusion Summer Study Report,* 2003. Available online at http://www.pppl.gov/snowmass_2002/snowmass02_report.pdf. Accessed September 1, 2003.

[7] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program.*

in this chapter, in the section entitled "Setting Priorities to Strike the Balance"), and must include consideration of the U.S. fusion program goals and international fusion activities. Nevertheless, the committee agrees that, generally, the aggregate level of activity implied below is needed both to support the move to a burning plasma program and to maintain a vibrant, productive domestic research program that is making progress toward the long-range goal of establishing the knowledge base for fusion energy.

Directly Support the Burning Plasma Program on ITER

ITER is a tokamak plasma-confinement device. A wide range of topics can be addressed in the domestic and world tokamak programs to prepare for and improve concepts for the operation of the ITER experiments. The preparation for and execution of a burning plasma experiment will be a multidecade activity. While there is every confidence that the ITER effort will be a successful scientific endeavor, a number of scientific and technological issues must be addressed to prepare for and make the best use of a burning plasma experiment. This section identifies key areas in which ongoing U.S. research and development can make significant contributions in order to gain the maximum benefit from participation in a burning plasma experiment. While these opportunities are discussed in the context of ITER, they are generally relevant to all burning plasma experiments.

- *"Pedestal" profiles in high-confinement plasmas.* Many of the highest-performance tokamak discharges operate in the high-confinement, or H-mode, regime, in which there is a steep gradient, or "pedestal," in both the temperature and density near the plasma edge (see Figure 4.2). Projections of both the stored energy and the fusion gain, Q, depend strongly on the height of this pedestal. Transport models are able to predict the thermal transport and resulting plasma temperature only if the pedestal height is taken from experiment observations. Work is needed to develop a first-principles theoretical understanding of this phenomenon.
- *Edge-localized modes.* The pedestal height in the H-mode is limited by so-called edge-localized modes (ELMs), which produce rapid bursts of heat and particles that can damage plasma-facing components. Mitigating these effects is an important topic for continuing research. Possible solutions now under study include new operating regimes with reduced or no ELM activity and ergodization of the edge magnetic field to control the pedestal. However, more experimental and theoretical work will be required before these techniques can be applied in the burning plasma regime.
- *Stabilizing neoclassical tearing modes.* At high plasma pressures, tokamak

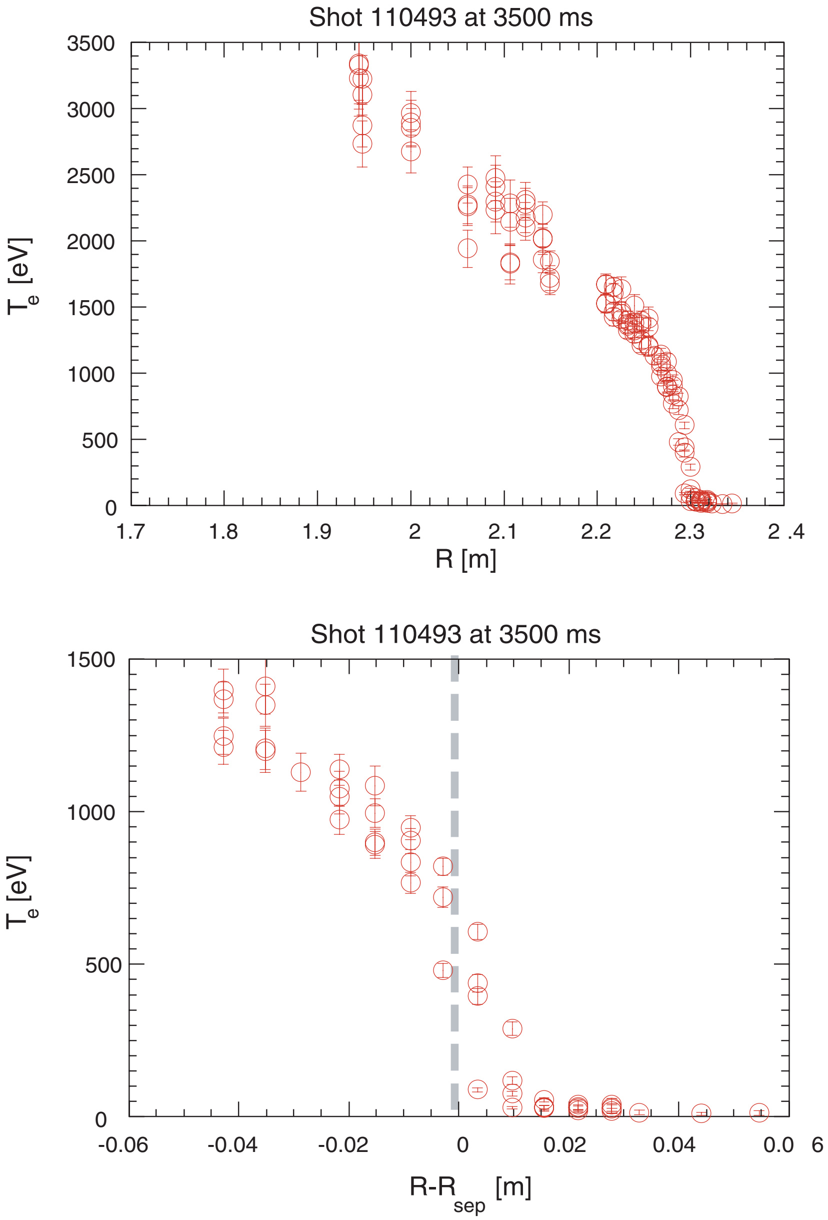

FIGURE 4.2 Temperature pedestal from a high-confinement mode regime discharge in the DIII-D tokamak. The increase in T_e across the last 4 cm at the outboard midplane is comparable to the temperature at the central density. NOTE: T_e is the temperature of the plasma, *R* is the radius from the center, and $R–R_{sep}$ is the distance from the edge of the plasma. Courtesy of General Atomics.

plasmas are susceptible to instabilities known as neoclassical tearing modes. These instabilities reduce the plasma confinement and projected fusion power output. It has been shown experimentally that these instabilities can be stabilized by injecting microwave power to drive currents at the location of the instability (see Figure 3.4 in Chapter 3).[8] To expand the ITER operating regime to higher pressure, techniques to determine quickly and reliably the location of these instabilities and to control the feedback current must be developed.

- *Steady-state and advanced tokamak operating regimes.* The tokamak would be much more attractive as a fusion energy source if it were able to operate in steady state. Developing the physics basis for long pulses before the initiation of ITER experiments would permit more effective use of ITER. Consideration is being given to hybrid operating scenarios that have improved confinement and stability limits. Successful demonstration of advanced tokamak scenarios would further expand stability limits, and additional current drive could permit discharges to be driven in true steady state, limited only by the cooling requirements of the device.
- *The density limit and high-density operation.* Modeling indicates that the energy gain and fuel purity of burning plasmas are favorably affected by increasing the plasma density. However, in present-day tokamaks, a limit to the plasma density that is proportional to the plasma current is observed. Very near this limit, confinement in H-mode plasmas is often observed to decrease, although some discharges with good confinement at densities significantly exceeding this limit have also been observed. Good progress is being made, both experimentally and theoretically, in understanding this limit. Continued research to understand this limit and the development of methods to exceed this limit would provide significant benefit to a burning plasma experiment.
- *Turbulent transport.* Understanding the transport in H-mode discharges and discharges with internal transport barriers could lead to large increases in energy gain in ITER and/or could permit operation at reduced values of

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[8] R.J. LaHaye, S. Günter, D.A. Humphreys, J. Lohr, T.C. Luce, M.E. Maraschek, C.C. Petty, R. Prater, J.T. Scoville, and E.J. Strait, "Control of Neoclassical Tearing Modes in DIII–D," *Phys. Plasmas* **9**, 2051 (2002); G. Gantenbein, H. Zohm, G. Giruzzi, S. Günter, F. Leuterer, M. Maraschek, J. Meskat, and Q. Yu, "Complete Suppression of Neoclassical Tearing Modes with Current Drive at the Electron-Cyclotron-Resonance Frequency in ASDEX Upgrade Tokamak," *Phys. Rev. Lett.* **85**, 1242 (2000).

plasma current and magnetic field. Understanding plasma turbulence is a key unsolved problem and one of the grand challenges in plasma physics. Exciting progress has occurred in this area over the past two decades. A working model of ion turbulence and the associated plasma transport has been developed. It is capable of reproducing the general characteristics of the turbulence and the resulting temperature profiles, but requires detailed testing by experiments. In contrast, no such model exists for turbulent electron transport, particle transport, and momentum transport. Associated with these phenomena is the need to understand the generation of electric fields in the plasma—these can either be spontaneously generated or externally driven—since they can profoundly affect the turbulence and thus the resulting plasma confinement. Theoretical models and experimental measurements for short-wavelength turbulence, which is predicted to play the most important role in electron transport, are just beginning to be developed. Similar efforts are under way with respect to turbulence in the important plasma edge region. Further progress in this area will also require additional theoretical and computational efforts and new measurements of the properties of the turbulence.

- *Tritium retention in plasma-facing components.* The present ITER design uses carbon-composite materials in the divertor, but the erosion of carbon and the deposition of tritium-laden carbon could make unusable much of the tritium inventory. Currently, two approaches are being pursued to address this issue. One approach is to better understand the erosion, transport, and redeposition of carbon and to devise mechanisms to remove the tritium from co-deposited carbon. The other approach involves the development of tungsten (or similar high-Z) plasma-facing components capable of both withstanding large pulsed-heat loads and producing plasmas with low levels of high-Z impurity radiation. Further research on this problem is needed before deuterium-tritium (D-T) plasmas are studied in ITER.
- *Disruption avoidance and mitigation.* Disruptive plasma terminations can occur as a consequence of exceeding magnetohydrodynamic (MHD) stability limits or through control or hardware failure. Research has now been successful in developing a disruption-mitigation technique using the injection of high-pressure noble gas.[9] Further research will extend the applicability of these results to larger devices. A related issue is that of determining

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[9] D.G. Whyte, T.G. Jernigan, A. Humphreys, A.W. Hyatt, C.J. Lasnier, P.B. Parks, T.E. Evans, M.N. Rosenbluth, P.L. Taylor, A.G. Kellman, D.S. Gray, E. M. Hollmann, and S.K. Combs, "Mitigation of Tokomak Disruptions Using High-Pressure Gas Injection," *Phys. Rev. Lett.* **89,** 055001 (2002).

safe limiting values for the plasma operating parameters. Reliable triggers are under development to initiate disruption mitigation in the case of an unexpected abnormal event.[10]

- *Divertor development.* The capabilities of ITER depend on divertors that can handle large heat and particle fluxes while maintaining plasma purity. The current ITER divertor is designed to operate at relatively high plasma densities. To explore alpha physics and steady-state operating scenarios, divertor solutions at lower plasma densities with improved heat-flux capabilities should be developed using techniques to cool the edge plasma through seeded-impurity radiation.
- *Plasma-facing components.* Plasma-facing components are one of the key issues for additional R&D. Designs that have been proven on small scales must be further developed for fabrication using large-area manufacturing techniques. Further testing will be needed to verify that these techniques are reproducible and reliable. This R&D should be done in the 5 years or so before the components are fabricated.
- *Diagnostic development.* The ITER program calls for a sophisticated set of measurement techniques capable of surviving in a hostile radiation environment. More diagnostic design is needed in order to integrate diagnostics into the ITER plan while maintaining the shielding requirements within the ports. Engineering R&D is needed to ensure the reliability of materials (ceramics and optical and insulating materials) and components (bolometers, probes, mirrors, and shutters) in the ITER radiation environment. New measurement techniques must also be developed; for example, a method is needed to measure the confined and escaping alpha-particle distributions in the burning plasma. These techniques must be developed and tested on ongoing experiments to avoid costly delays in undertaking burning plasma experiments.
- *Tritium breeding blankets.* To ensure a sufficient tritium supply for follow-on devices, it is highly desirable to initiate research on tritium breeding on the ITER device. Since the tritium-breeding test blanket module for ITER will be a first-of-a-kind device, significant R&D is needed to verify its design and to predict breeding performance accurately. It would be advantageous

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[10] D. Wroblewski, G.L. Jahns, and J.A. Leuer, "Tokamak Disruption Alarm Based on a Neural Network Model of the High-Beta Limit," *Nucl. Fusion* **37**, 725-741 (1997); D.G. Whyte, T.C. Jernigan, D.A. Humphreys, A.W. Hyatt, C.J. Lasnier, P.B. Parks, T.E. Evans, P.L. Taylor, A.G. Kellman, D.S. Gray, and E.M. Hollmann, "Disruption Mitigation with High-Pressure Noble Gas Injection," *J. Nucl. Mater.* **313-316**, 1239-1246 (2003).

to start R&D on the test blanket module immediately after the ITER negotiations are completed.

The committee believes that the activities described above will play a central role in the domestic fusion program, in coordination with the international partners, in supporting the preparation for and operation of a burning plasma experiment. These activities define a substantial part of the role that tokamaks can play—with associated theory, diagnostic, and technology development—as ITER is constructed and operates.

The following subsections address the role of the four largest concept-optimization research programs along with other key research activities and summarize specific scientific goals for each of them.

Develop an Understanding of Paths to Advanced Tokamak Regimes

The advanced tokamak (AT) is a variation of the tokamak confinement configuration. It uses active profile optimization and MHD mode stabilization to provide, in principle, steady-state operation at high pressure and enhanced confinement, with the self-generated bootstrap current sustaining almost the entire plasma current. The AT is a leading candidate for a first-generation design of a fusion reactor. It employs active control of accessible plasma profiles (e.g., heating, density, pressure, and so on) to provide this enhanced performance. The integration of these varied tools and characteristics into a self-consistent scenario is a major focus of research. AT experiments in smaller facilities with a range of control tools and plasma-shape capabilities will complement and guide the AT studies in the burning plasma program and in ITER itself. In addition, these experiments will expand to investigate wider ranges of plasma shape and stability limits so as to test the fundamental understanding of possible AT regimes.

In summary, the major goals of the advanced tokamak program are these:

- To demonstrate integrated advanced tokamak scenarios with current sustained dominantly by the bootstrap current and enhanced confinement at high pressure, and to develop predictive understanding of AT regime accessibility and control;
- To develop techniques to control plasma current, pressure, flow, and transport profiles while maintaining plasma stability in this highly nonlinear, self-organizing regime;
- To develop radiative divertor operation regimes that can minimize power deposition and maintain helium pumping in low-density AT operational regimes compatible with external current drive;

- To test theories of MHD instability control and develop techniques to allow the active avoidance of unstable boundaries resulting from resistive wall modes and neoclassical tearing modes; and
- To demonstrate techniques to ameliorate the effects of abrupt plasma disruptions if boundaries are breached.

Test the Effects of Extreme Toroidicity in the Spherical Torus

The spherical torus (ST) is attained when the toroidal aspect ratio of a tokamak is reduced toward its absolute lower limit (i.e., the hole in the center of the torus is reduced to a small fraction of the plasma radius). The study of ST plasmas is of interest because it challenges tokamak-based physics understanding at the limits of toroidicity and shaping. The ST plasmas near these limits are characterized by the following: stable access to very high normalized plasma pressure (plasma pressure comparable to magnetic field pressure), suppressed electrostatic turbulence due to strong rotation shear, plasma of very high dielectric constant strongly affecting wave–plasma interactions, and high particle trapping near the plasma edge. The ST may provide a reduced-cost path to the development of fusion energy if the central induction solenoid can be eliminated through the development of start-up and sustainment techniques.

In summary, the major goals of the spherical torus program are these:

- To test MHD stability theory at conditions of extreme toroidicity in order to elucidate physics of very high normalized plasma pressure and high fraction of self-generated (bootstrap) currents, strong magnetic shear, and strong plasma rotation relative to the Alfvén velocity;
- To validate turbulence theory in the extreme condition of high pressure with possible electromagnetic effects—using unique features of the ST, such as strong field line curvature, strong and reversed-field gradients (magnetic well), and high edge magnetic shear to test fundamental theories of turbulence and transport;
- To explore the interactions of strongly supra-Alfvénic energetic particles and MHD instabilities such as the toroidal Alfvén eigenmodes with spectral characteristics different from those found in tokamaks;
- To extend the understanding of plasma edge instabilities and transport to regimes of high particle trapping and strong field line expansion; and
- To demonstrate plasmas dominantly sustained by the bootstrap current and initiated without an internal transformer.

Investigate Sustainment and Enhanced Confinement in the Reversed-Field Pinch

The reversed-field pinch (RFP) is a toroidally symmetric configuration in which the magnetic fields are generated mainly by internal plasma currents. These currents cause the toroidal field to change direction near the plasma edge region (hence the name). The equilibrium results from a self-relaxation of the plasma to this reversed-field state; the relaxation is driven, to date, by a dynamo effect. This phenomenon provides a laboratory test of nonlinear plasma-relaxation properties found in nature and the laboratory. An RFP reactor may present attractive properties, arising from low magnetic fields and high plasma pressure (relative to the magnetic pressure). The RFP is at a level of development considerably less mature than that of the tokamak; several areas of investigation are required in order to evaluate its potential for fusion and to provide laboratory tests of self-organizing plasmas with relevance to astrophysical phenomena.

In summary, the major goals of the reversed-field pinch program are these:

- To demonstrate the generation of RFP equilibria without a dynamo driven by large-scale MHD instabilities, using efficient current sustainment techniques;
- To evaluate the confinement properties of the RFP in the absence of large-scale MHD fluctuations;
- To investigate the ability to improve the RFP via control of the plasma geometry and/or profiles and via control of the spectral properties of fluctuations;
- To investigate the stability limit of the plasma pressure and to develop methods to increase it using feedback stabilization; and
- To improve the understanding of the physics that is common to the RFP and astrophysical plasmas.

Explore the Potential for Passive Stability and Steady-State Operation in Three-Dimensional Stellarators with Underlying Magnetic Symmetry

The stellarator is a toroidal configuration in which the magnetic fields needed for plasma confinement and stability are generated by twisting the shape of external coil sets to produce closed magnetic-flux surfaces. The stellarator does not require externally driven plasma current. This allows very efficient steady-state operation and, potentially, greatly reduced susceptibility to current-driven instabilities. Advanced stellarator concepts suggest that confinement properties at least comparable to those of tokamaks can be achieved with underlying symmetries in the magnetic field coordinate system. The near-term focus is to test benefits predicted with magnetic symmetry using three-dimensional shaping, examine more-compact stellarator configurations, and explore plasma shapes that are predicted to be able to operate at high normalized plasma pressures.

In summary, the major goals of the stellarator program are these:

- To test theory of MHD stability boundaries in three-dimensional plasmas, varying the contribution from plasma currents, and to explore the sensitivity of the plasma pressure stability limit to strong three-dimensional shaping;
- To test the understanding of current-driven disruptive instabilities in stellarators;
- To demonstrate the predicted ability to achieve tokamak-like confinement properties in stellarators with magnetic symmetry;
- To test theories of turbulence-driven transport in three-dimensional magnetic configurations of varying symmetry; and
- To explore the ability to access improved confinement regimes in stellarators—the strong rotational damping, which is drastically reduced in stellarators with symmetry, provides a test of the mechanisms of turbulence suppression.

Explore Novel and Emerging Fusion Science and Technology Concepts

Small-scale experiments can address some unique fusion research issues that may be relevant to near-term applications of fusion science and technology, or allow the study of speculative emerging concepts for advanced fusion systems. These experiments and their associated theory efforts address basic issues of formation, equilibrium, and stability. The concepts promise engineering simplifications (for example, simpler plasma-wall interfaces) and potentially more-compact fusion systems that could be compatible with novel chamber technologies such as lithium metal walls. Many of these systems are small enough to reside in university laboratories; thus they efficiently contribute as workforce recruitment and training facilities as well as being research devices.

One class of such investigations addresses configurations with external topology that is spherical rather than toroidal; no electromagnets penetrate the plasma volume. The spheromak and field-reversed configuration (FRC) are in this class. Similar to the reversed-field pinch, they rely on self-organizing properties to establish closed flux surfaces for confinement, and they are susceptible to large-scale MHD instabilities. Fusion science research opportunities in this area include the following: exploring stability and confinement characteristics of spheromak plasmas in a regime in which the electron collisional path length is comparable to the plasma dimensions; developing an understanding of the physics of using linked magnetic flux tubes to form and sustain these strongly self-organized plasmas; and determining the origin of experimentally observed stability in the FRC at low collisionality.

A second class of small experiments addresses novel, less-developed fusion and plasma confinement concepts that expand the knowledge base of basic plasma stability and confinement and offer specific advantages for speculative new fusion concepts. The issues under investigation naturally evolve over time, but they include these, among others: the study of high-pressure plasmas in a simple magnetic-dipole configuration, the use of the magnetic compression of physical liners to compress and heat small FRC plasmas to thermonuclear conditions on a pulsed basis, and the use of strongly flowing and/or rotating plasmas to stabilize simple cylindrical plasma configurations.

Develop Fusion Technologies to Enable Innovative Fusion Science Experiments and Provide Attractive Long-Term Reactor Concepts

As discussed earlier, the pursuit of a burning plasma experiment requires the development of new technologies to produce and study burning plasmas in ITER and facilitates the testing of critical fusion technologies in a reactor-scale environment. In addition to developing those technologies related to the burning plasma program, the domestic fusion program, in collaboration with international partners, must advance the knowledge base for fusion energy by addressing issues in three main areas: plasma technologies in support of advanced fusion science experiments, plasma chamber technologies, and fusion materials. Regardless of the degree of commitment to developing a fusion reactor in any specific time frame, research activity in these areas supports the long-range goal of developing attractive fusion concepts.

The development of low-activation materials that can survive in a fusion environment is a critical issue for the long-term suitability of fusion as an energy source. Such materials are not critical to the success of the ITER experiment, but the availability of appropriate materials impacts the performance, safety, and overall costs of an eventual fusion system. Consequently, this is an active area of research in the international program. Relative to Japan and Europe, the United States has a relatively small fusion technology program with concentration in low-activation materials and high-heat-flux components. Opportunities exist for the U.S. program in collaboration with international partners to make significant contributions to evaluating the properties of varying alloys and composites.

To realize the advantages of compact confinement systems that are being investigated for future fusion systems, novel plasma chamber technologies may be required to handle very high heat loads. Innovative chamber technologies using flowing liquid walls and high-power-density solid walls are under investigation.

Partner with International Collaborators

It is important to recognize that R&D in the U.S. fusion program needs to be coordinated with the international partners of the United States and with the ITER process. U.S. tokamak programs are already loosely integrated with equivalent and larger facilities in the European Union and Japan through the International Tokamak Physics Activity (ITPA), which identifies and promotes areas of cross-fertilization and comparative experiments. Recently there has been significant international planning of "joint experiments" to address critical scientific issues identified by ITPA groups. These other international tokamak programs—that is, in addition to the ITER program—are also pursuing many of the issues discussed above.

The stellarator, spherical torus, reversed-field pinch, and tokamak programs all have International Energy Agency agreements for international coordination and collaboration. Each of these respective communities holds regular meetings. In each of these cases, there is a high degree of sharing of personnel and tools between the U.S. and non-U.S. programs.

The U.S. support of the ITER endeavor and the entire U.S. domestic program will require tighter coordination and collaboration. The ITPA efforts will provide a natural bridge to coordinate the U.S. tokamak activity with related international efforts and thus will optimize the return to the United States from its investment in the ITER program. Increased international interactions could also benefit the configuration-optimization research programs and should be strongly encouraged.

THEORY AND COMPUTATION

One important goal of a burning plasma experiment is to use the knowledge gained to predict performance in other toroidal confinement devices (i.e., potential candidates for subsequent steps toward useful fusion energy). However, transferring burning plasma knowledge to these configurations will require a detailed theoretical understanding of the fundamental physical processes involved. If the U.S. magnetic fusion program is to take full advantage of participation in ITER, it will be necessary to develop a first-principles understanding of the phenomena that determine ITER's performance. This understanding will require the development of improved models of the edge plasma, transport barriers, density limits, core confinement, and MHD instabilities. Success in this endeavor will require a continued program of experiment, theory, and modeling, including a strong experimental program on ITER itself.

The progress of fusion science has relied heavily on the development of theory and extensive numerical computation and simulation. It has long been recognized that the complexity of the burning plasma problem was so great that purely analytical methods are not capable of yielding the desired fidelity. Computer models of parts of the entire system were developed (the so-called reduced description), allowing a piecemeal simplification of the complex physics. This approach has led to a new level of understanding and has served the fusion program well. Much of the work has been carried out by individual investigators or small teams and has benefited from access to computational resources ranging from workstations to supercomputers.

Recent efforts along these lines have played an essential role in the decision to move forward with rejoining the ITER negotiations. Indeed, simulations in both fluid and kinetic regimes were able to demonstrate instability control or avoidance in substantial agreement with experiment. A critical lesson drawn from these efforts is the importance of tight coupling of theory, experiment, and computation.

However, significant near-term challenges remain in the areas of plasma edge physics, turbulence on transport timescales, global macroscopic stability, and their extensions to a burning plasma regime. The problem of modeling systems with widely disparate time and space scales has been dealt with so far by the use of reduced descriptions, but at some stage of investigation, the coupling between the reduced regimes becomes important and presents formidable challenges.

An example of the complexity involved is what is called plasma edge physics. The plasma edge, the region at the outer boundary of the plasma, is one of rapidly varying density; it strongly influences stability. For a proper treatment of turbulence, an understanding of this region is necessary, and it determines divertor design. The plasma edge is not adequately treated in the current, simplified models. This defect stems from the need to deal with a kinetic-theory description in which the mean free paths vary dramatically, spatial gradients are large, boundary-condition fixation is essential but often incompletely known, and complicated chemistry and wall effects prevail.

Going forward, a program in theory and simulation must rely on a marriage of advances in information technology, plasma science, applied mathematics, and future developments in software. The emergence of grid computing may be an enabler of this kind, although progress in numerical algorithms can be as fruitful as improvements in hardware in dealing with large problems. Since many of these developments are expected to arise from university-based research programs, these activities require continued support. Emerging from these efforts will be new insights and algorithms that will improve the simulations which will eventually have to be done on the largest of the supercomputers. One daunting goal is the development of integrated programs that reliably model in detail most of the fusion machine. The computation and simulation part of the fusion program will need attention and possible expansion for the ITER program.

It may be that other areas of science, heavily dependent on computation, have developed tools that can be adopted for the progress of fusion science. In particular, the struggle to improve weather forecasting by even one day has given rise to techniques of ensemble averaging, reanalysis, treatment of mesoscale and synoptic regions, and data assimilation to drive models. The approach used by the climate community has also been successful in permitting widely separated research groups to utilize common models as well as providing a testbed for new developments.

In the field of computation and simulation relating to fusion technology development, one area of potential promise is the marriage of nanoscience techniques and advanced computation to help in the development of materials modifications such as dispersion strengthening, which could allow for higher-temperature operation. Modeling material damage from energetic fusion neutrons is an especially challenging problem that involves molecular dynamics, mesoscale modeling, self-healing, and other areas, and combines the physics of different characteristic timescales.

WORKFORCE READINESS

In the era of a burning plasma experiment, the recruitment, training, and retention of scientific and technical talent constitute a crucial element of the fusion and plasma research and development effort. The nation's research universities and national fusion facilities will play a critical role in filling these personnel needs. The decision to participate in a large burning plasma experiment such as ITER carries with it an increased level of commitment to an extended program in fusion research and development. Since the preparation for ITER and the execution of its experimental program are expected to cover more than two decades, the technical personnel activities associated with this effort must be sustained and ongoing. With any increased U.S. investment in fusion in the era of a burning plasma experiment, the development and maintenance of the most highly qualified personnel in plasma and fusion science and engineering become even more important than they have been until now. Training the plasma and fusion workforce has two related components: a broad university education in basic science and engineering and the more specialized training in technical areas specific to fusion and the burning plasma experiment.

Aging Workforce and Dwindling Supply

New personnel will be needed not only for a burning plasma experiment but also to maintain the supporting educational and research programs in the universities and national laboratories. The current demographics of the fusion science and plasma physics workforce point to potentially significant problems.

The NRC FUSAC report noted that the fusion and plasma science workforce in the universities and at large fusion facilities is aging, with too few young people entering the field. The same report also noted that the nation's fusion and plasma science programs are concentrated in relatively few universities.[11] Responding to the FUSAC report and to earlier studies, the Office of Fusion Energy Sciences took important actions that will help to increase the talent pool and ensure the vitality of the basic plasma research efforts in the universities. It established a Principal Young Investigator program in plasma science, as well as supporting several new small-scale experimental programs through the Innovative Confinement Concepts activity. It also took a leading role in creating the Department of Energy/National Science Foundation (DOE/NSF) program in basic plasma physics. In view of the need for supplying a sufficient workforce as the U.S. fusion program enters the burning plasma era, these issues are discussed briefly here.

The rate of plasma science Ph.D. production is summarized in Figure 4.3. The production rate of Ph.D.'s in plasma and fusion science shows a decline since the mid-1980s. The decline shown in Figure 4.3 generally tracks—although it starts approximately 3 years after—the onset of a similar decline in the funding level of the U.S. Office of Fusion Energy Sciences Program. In contrast, the rate of Ph.D. production over all fields of physics shows no such decline, consistent with approximately constant funding for physics as a whole. The flattening of the fusion budget over the past several years suggests that plasma and fusion Ph.D. production may soon flatten, or even rise in response to the increased number of university research initiatives started in the past decade. Nonetheless, the trend continues to be worrisome.

Of course not all new entrants into the field need come from university plasma programs, and in fact it is desirable to have an influx of new scientists from other areas of science and technology as the field moves forward. The U.S. fusion program has a long history of attracting talented scientists and engineers who were educated in other fields, such as high-energy physics or nuclear engineering. Such cross-fertilization from other technical fields provides valuable infusions of talent

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[11] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program.*

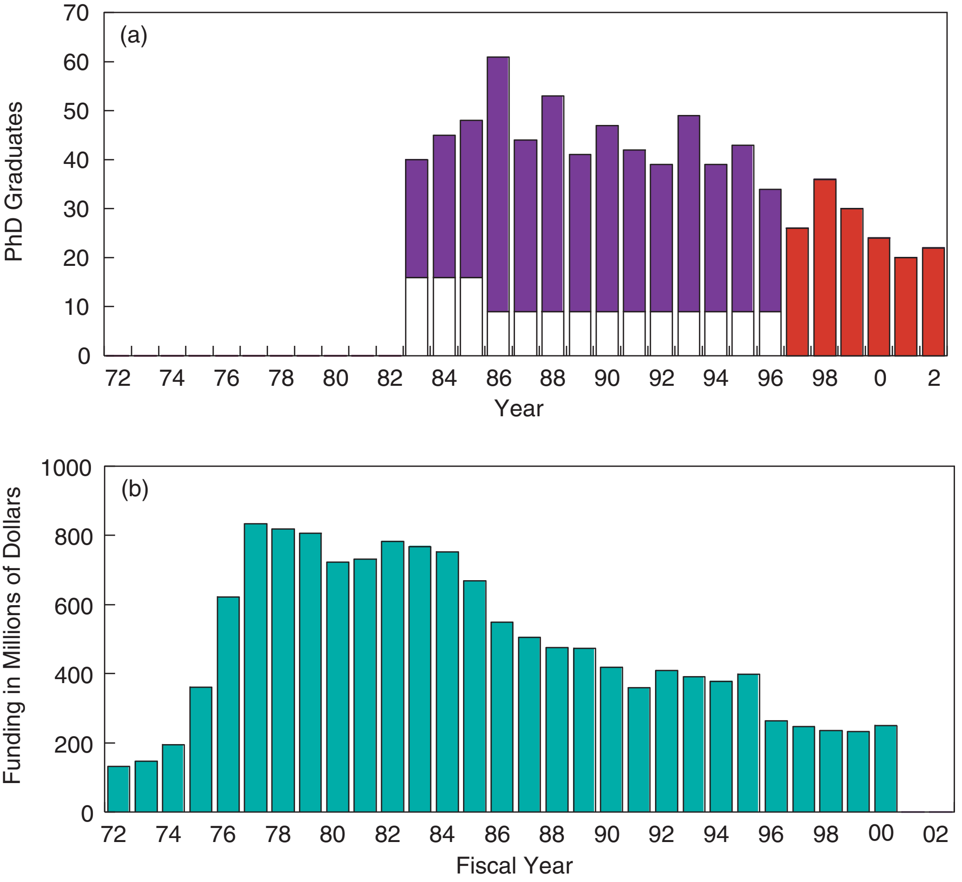

FIGURE 4.3 (a) Total plasma science Ph.D. production per year from 13 institutions with major plasma science programs (red and violet) over the past 20 years. A decline of approximately 50 percent in the past decade is observed. Data from 1997 and later (shown in red) include all responding institutions. Pre-1997 data from some institutions are incomplete. The violet shows Ph.D. production from those institutions with data. Ph.D. production for the remaining institutions (open blocks) was assumed to equal the level for the most recent year with data. This assumption likely underestimates the pre-1997 Ph.D. production. (b) Funding level of DOE Office of Fusion Energy Sciences program in constant FY00 dollars. SOURCE: E. Scime, K. Gentle, and A. Hassam, *Report on the Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States*, College Park, Md.: University Fusion Association, 2003. Courtesy of the University Fusion Association.

and diverse approaches to fusion problems. Likewise, not all students who do Ph.D. research in plasmas and fusion pursue careers in fusion. It is estimated that these two fluxes tend to cancel one another, although hard data are not available at the present time.

The age distribution of U.S. fusion science faculty as compared with that of physics faculty in all fields is shown in Figure 4.4. The ratio of faculty in the 55-to-75 age bracket to faculty in the 30-to-50 age bracket is about 1.5 for the fusion science faculty and 1.1 for all physics faculty. As shown in part (a) of the figure, this aging of fusion science faculty is most pronounced when the older, more established, and larger institutions are considered alone. Current hiring plans will not remedy this situation. To quote the University Fusion Association report, "Hiring trends at [these] larger institutions suggest that recent and projected fusion science hiring at larger institutions is down. . . . [T]he hoped-for hiring in fusion science over the next five years indicates a hiring-to-retirement ratio of at most two hires for every three retirements."[12]

As shown in Figure 4.5, the age distribution of the scientific and engineering workforce at the nation's three largest fusion laboratories—General Atomics, the Princeton Plasma Physics Laboratory, and the Massachusetts Institute of Technology—is similarly skewed toward older ages. Replacing this demographic bulge in the fusion community as the program moves into the burning plasma era will place significant demands on workforce development.

The available data indicate that the scientific and technical workforce in plasma and fusion science is aging markedly. There is a possibility that too few young people will be entering the field. In the worst case, it is possible that a significant fraction of the U.S. participants in the ITER effort will be near the end of their careers. Predictions over the long range are uncertain in that they depend on overall program development, but it is clear that the situation merits deeper investigation and continuing scrutiny to ensure a sufficiently large, high-quality workforce in the fusion science program.

Recruitment and Basic Scientific and Technical Education

At least two factors affect the recruitment of new personnel into the plasma and fusion science workforce. The first is the relatively small number of U.S. plasma and fusion programs, discussed above. Increased educational and research opportunities in plasma science and the continued expansion of outreach efforts

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[12] E. Scime, K. Gentle, and A. Hassam, *Report on the Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States,* College Park, Md.: University Fusion Association, 2003, p. 1.

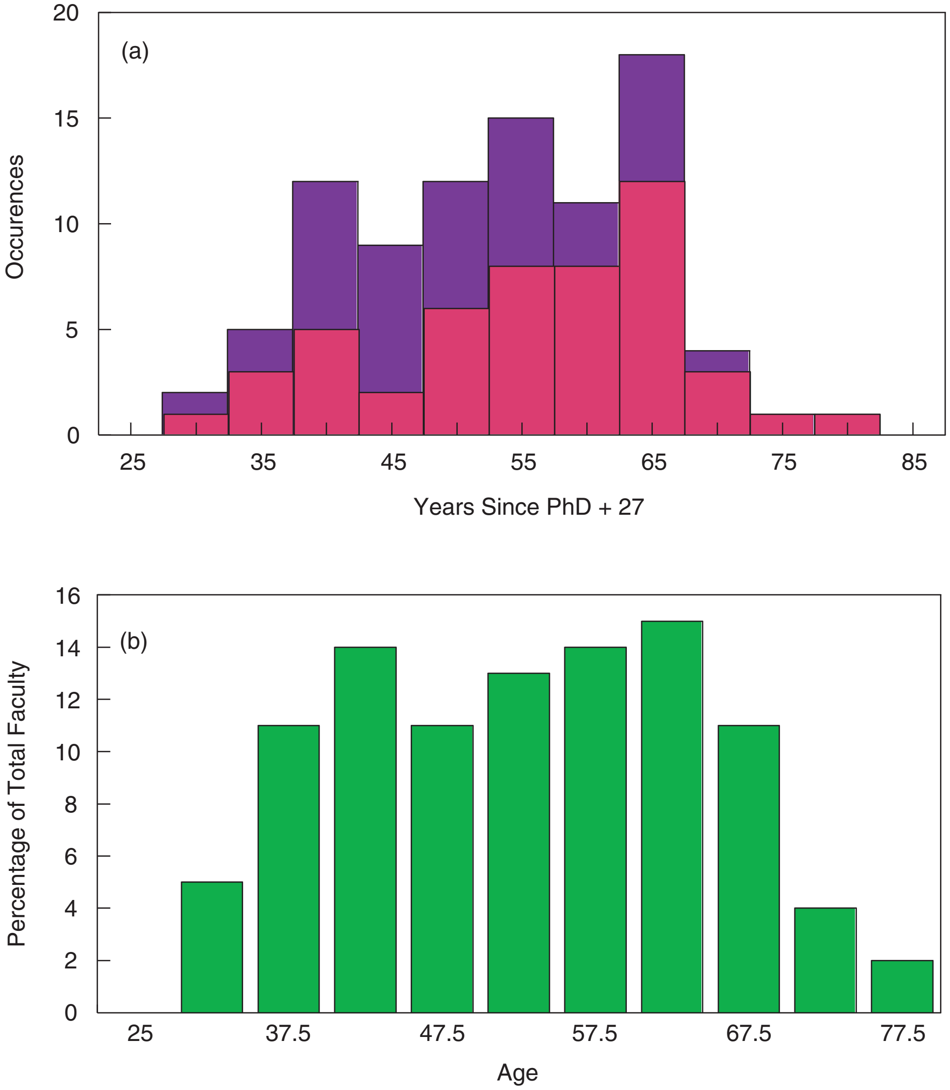

FIGURE 4.4 (a) The age distribution of fusion science faculty at 23 institutions with active plasma and fusion science programs. Shown in red are data from six major centers of plasma physics (Massachusetts Institute of Technology, University of Maryland, University of Wisconsin at Madison, University of Texas, University of California at San Diego, and University of California at Los Angeles). (b) The age distribution of physics faculty in all fields in U.S. colleges and universities. SOURCE: E. Scime, K. Gentle, and A. Hassam, *Report on the Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States*, College Park, Md.: University Fusion Association, 2003. Courtesy of (a) the University Fusion Association and (b) the American Institute of Physics.

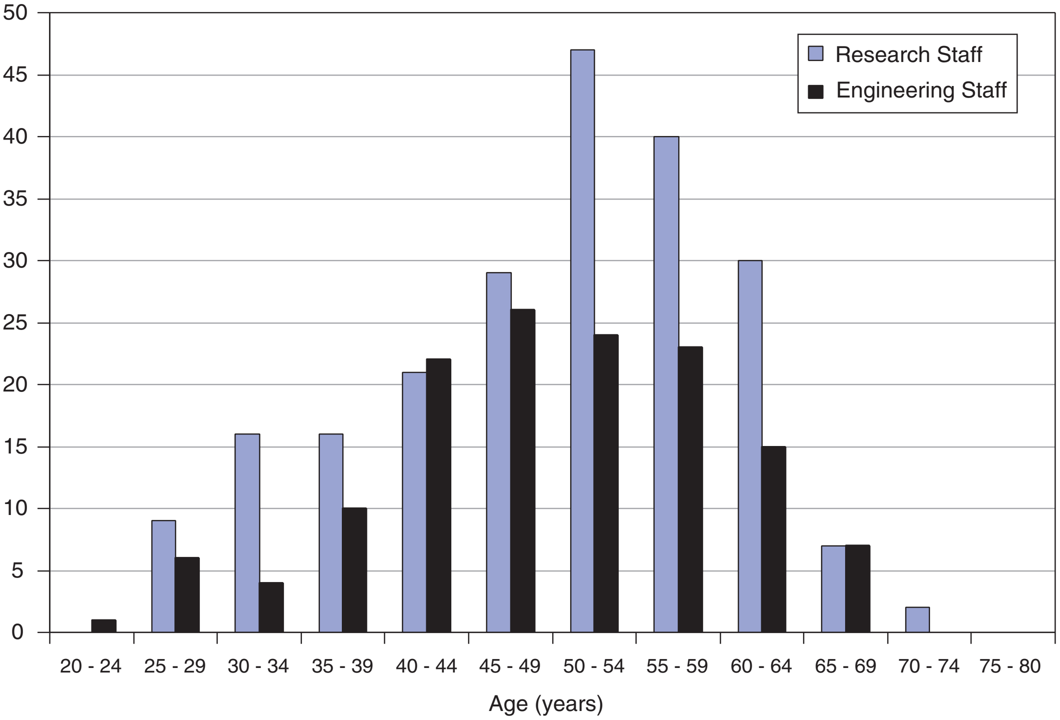

FIGURE 4.5 Age distribution of the scientific and engineering staff at the nation's three largest fusion facilities: Princeton Plasma Physics Laboratory, General Atomics, and Massachusetts Institute of Technology. This population comprises roughly one-half of the professional research staff supported by the fusion science program, excluding the university population, and is reasonably representative of the community as a whole.

by the fusion community (for example, at the undergraduate level) would help. The aim of these efforts should be to provide a high-quality education in the broad range of areas relevant to fusion science and technology and to attract excellent talent to the field.

The second factor affecting recruitment is the availability of challenging job opportunities. Scientific and technical talent gravitate toward exciting opportunities. In other words, new initiatives and sustained efforts attract talent. With a time lag of 5 to 7 years from the start of new initiatives to the first students' completion of their training, personnel needs take time to fill. This development time also argues for a sustained long-term commitment. Because of the expected scale of a burning plasma experiment, the ITER effort could provide such an opportunity for a national initiative that would help attract and sustain talent, drawing in personnel from areas of science and engineering beyond traditional plasma and fusion science.

The breadth and quality of training will also be important. The more than two decades of future activity on a burning plasma experiment will be accompanied by significant changes in science and technology. The well-trained fusion scientist or engineer of the coming decades will require knowledge of concepts and techniques that do not now exist. The hardware and techniques for engineering and scientific research can be expected to change in fundamental ways. Examples involve expected advances in computational techniques, laser and other radiation sources for probing plasmas, sensors, measurement techniques, materials, manufacturing techniques, interfacing of computers to experiments, and so on. Furthermore, many of the scientific concepts used to describe physical phenomena will be qualitatively more sophisticated a decade or two hence. Examples of areas currently undergoing dramatic changes include the modeling of nonlinear processes ranging from plasma heating to magnetic reconnection and models of plasma turbulence and turbulent transport. These and many other areas are likely to change dramatically in the decades of the burning plasma experiment. Thus, the basic training of fusion scientists and engineers in broad areas of physical science and engineering must continue to be an integral part of the fusion program.

Increases in funding for university programs potentially can have a disproportionately large impact in various ways. Such increases can have an impact on recruiting new talent, on providing broad training of fusion scientists and engineers, on expanding the ties between the fusion community and other areas of science and technology research, and on leveraging more effectively the U.S. investment in burning plasma R&D to generate new ideas and exploit progress made in other fields.

The committee believes that the U.S. fusion program should make a focused effort to analyze and address personnel needs required for the following: (1) revitalizing the fusion workforce, (2) building a burning plasma device, and (3) conducting burning and non-burning-plasma experiments (see the subsection entitled "The Role of the Universities: Research, Education, and the Fusion Workforce" in Chapter 1). If a dearth of personnel is found, the fusion program could consider several possible actions that would aid in resolving this problem. Options might include highlighting a program of nationally competed, prestigious fellowships in fusion science and technology to attract outstanding Ph.D.'s to the field. To infuse new talent into the aging university plasma and fusion faculties, the fusion program could consider providing increased matching salary and start-up funds for new assistant professors in plasma and fusion science. Expanded use of DOE Office of Fusion Energy Sciences fellowships at the national fusion facilities could encourage the participation of graduate students in larger-scale activities in fusion science and technologies. Similarly, establishing sizable university-based user groups to collaborate on national facilities could increase university involvement and offer unique graduate study opportunities. Finally, broadening the available talent pool and expanding training opportunities for students and postdoctoral researchers could be aided by increased support for the NSF/DOE plasma science initiative[13] and the DOE/NSF Fusion Science Center Program that is scheduled to begin with a first center in FY 2004.

Ensuring the continuing vitality of the fusion science and engineering research activities in the universities is critically important. Projects that have traditionally been the major source of trained personnel for the fusion program include smaller-scale confinement experiments, diagnostics development, theory and modeling, and technology research. Recognizing that much of fusion science research is moving to team-oriented research on larger, shared facilities, it is also important that the university community have the opportunity to become integrally involved in these regional, national, and international fusion research activities.

Specialized Training in Fusion Technology

Fusion and plasma physics of the future, and particularly the burning plasma experiment, will involve highly specialized technical endeavors. In many areas, the traditional doctoral degree in plasma physics or engineering will need to be augmented by training at a fusion-related facility (for example, a large tokamak or related facility, or ITER itself). This more specialized training will be required for work both on the burning plasma experiment and at other fusion-grade plasma research and development facilities. Specialized training is needed in all areas. Examples include tokamak operation and control, specialized diagnostics, and specific research topics such as fusion alpha physics, Alfvén modes, transport, and magnetohydrodynamic stability. This training can best be done by making full use of the range of U.S. and international plasma and fusion facilities.

The committee finds an immediate and critical need for technically trained personnel to begin to build the burning plasma experiment. The fact that there has

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[13] The NSF/DOE initiative is currently funded at a level of $4 million per year. The 1995 NRC plasma science study recommended the establishment of this program at $15 million per year, and the NRC FUSAC report endorsed this recommendation. (See National Research Council, *Plasma Science: From Fundamental Research to Technological Applications*, Washington, D.C.: National Academy Press, 1995, p. 3; and NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, p. 5.)

been only one fusion device, of modest size, built in the past decade has led to a critical shortage of trained fusion engineers. While the R&D effort associated with the ITER Engineering Design Activity helped bridge this gap, U.S. involvement in this activity ended 5 years ago. The fusion environment presents unique and challenging technical problems—for example, spatially and temporally varying magnetic fields, large transient electromechanical stresses, copious amounts of atomic hydrogen, high heat fluxes, a limited range of suitable materials that minimize plasma contamination, and significant fluxes of high-energy neutrons. The harsh and demanding burning plasma environment requires training personnel with highly specialized skills so that they are capable of developing practical engineering solutions and affordable components for the burning plasma experiment.

The bidding process for the ITER work packages is now under way. It nominally requires proven experience in the technologies and devices being bid. Owing to the recent deemphasis of fusion technology, the United States does not now have the desired level of proven experience in most areas. As shown in Figure 4.6, the number of personnel involved in fusion technology R&D in the United States has declined by about 50 percent since the mid-1990s, along with the budget for fusion technology. Specialized facilities at universities and national laboratories have been constructed for technology research, but they are currently underutilized. If the United States is to make the most of full partnership in ITER, significant new activity must be supported to reinvigorate the U.S. fusion technology enterprise and to enable the United States to participate effectively in the construction of components for ITER. Such activity will also help position the United States to play a leading role in the follow-on steps toward useful fusion energy.

Consideration might be given in the U.S. fusion program to creating internships in fusion technology for established scientists and engineers in order to jump-start the training of new fusion personnel. The program could also consider increasing its involvement in industries that provide fusion-relevant technology. This type of increased involvement could benefit the discovery of new technology—such developments are more likely in an environment in which fusion-relevant hardware is developed and constructed on a regular basis. New hardware presents new technical challenges and stimulates new solutions to this type of forefront problem.

In summary, careful attention must be paid to the training of scientific and technical personnel for the fusion and plasma physics work in the foreseeable future. This will require increased outreach to talent pools and additional connections to the broader academic, scientific, and technical communities. It will require immediate attention to the training and retaining of fusion engineers capable of designing and building the many intricate components necessary for a

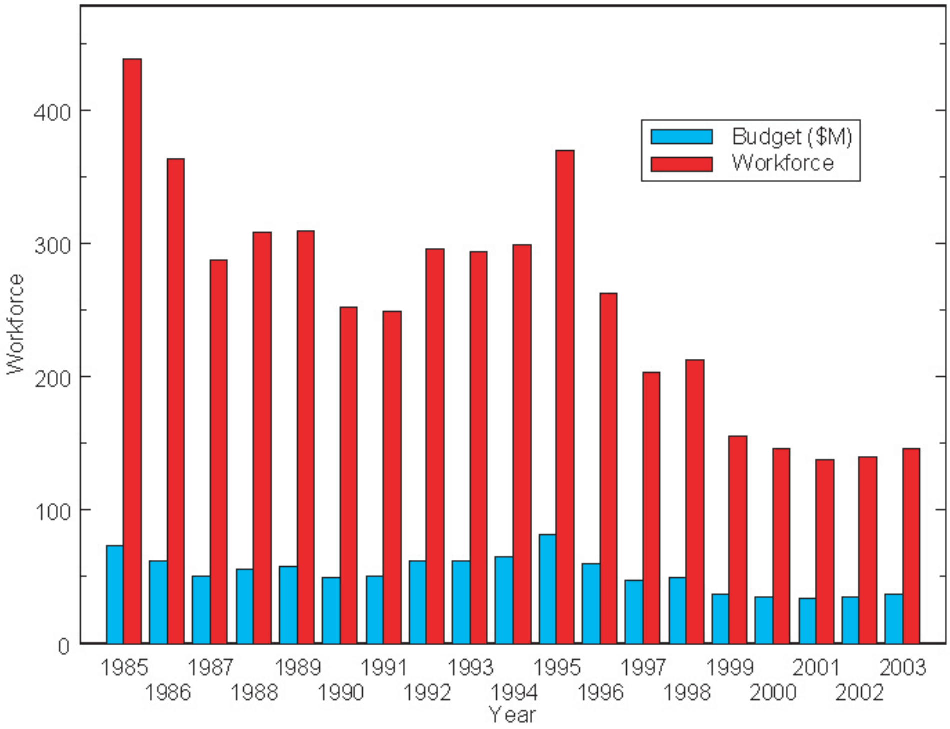

FIGURE 4.6 Trends in the fusion technology workforce and budget since 1985. The trend shows that the fusion technology workforce has sharply declined since the mid-1990s, roughly coincident with the deemphasis of technology when the United States left the ITER project. Not only is this population aging, but there is a concern that it may fall below the number of staff needed to optimize participation in a burning plasma experiment and gain maximum benefit from participation.

burning plasma device. It will also require a renewed and sustained effort to train and retain the highly specialized personnel necessary to create burning plasmas and to study fusion physics in them. These personnel must be trained not only in the fundamentals of basic plasma science, but also in technical areas specific to the study of burning plasmas.

PROGRAM STRUCTURE AND ITS EVOLUTION

Considering the previous discussions in this chapter and in Chapter 3, the committee believes it to be clear that, in order to look at the broad range of fusion science issues, the U.S. fusion program needs to support both the study of burning plasmas and a portfolio of non-burning-plasma, smaller-scale research efforts. These two thrusts are tightly coupled, and pursuing one at the expense of the other seriously weakens the entire enterprise. A strategically balanced fusion program must include theory programs, computer simulations, experiments with existing facilities, advanced diagnostic development, technology development, and support for alternate configurations, not only as support for the ITER effort, but also as the means of continuing to look toward the larger goal of developing the foundations for fusion energy.

This need for a U.S. fusion program that pursues burning plasma studies and addresses science issues beyond the burning plasma experiment itself has been affirmed by the fusion community's 2002 Snowmass study, by reviews from the DOE's Fusion Energy Sciences Advisory Committee (FESAC), and by outside reviews of the U.S. fusion program. Recognizing the diversified and balanced approach of the current program, the NRC FUSAC report says:

> An optimal fusion science program needs two components: experiments in non-burning plasmas to explore the large range of critical science issues which do not require a burning plasma; and experiments in burning plasmas. . . .[14]

While concluding that fusion science is on a par with other fields of physical science, the FUSAC study recommended that "increasing our scientific understanding of fusion-relevant plasma should become a central goal of the U.S. fusion energy program on a par with the goal of developing fusion energy technology" as the appropriate approach to fusion energy research.[15] As noted previously in this report, this committee reaffirms these recommendations as guiding principles for embarking on a burning plasma experiment.

The initiation of burning plasma experiments at a large facility will impact all levels of the U.S. fusion program. The ITER experiment, or indeed any burning plasma experiment, represents a significant new commitment by the United States to the development of fusion energy science. Given the magnitude of this step and the need to support it in full, it is clear that a new balance will need to be struck among the elements of the U.S. fusion program.

The discussion in this section addresses the breadth and structure of the fusion program that will be necessary to support the development and operation of a burning plasma experiment on ITER and to achieve a program in which the critical elements are in reasonable balance for the purposes of attaining the long-range

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[14] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program,* p. 53.

[15] NRC, FUSAC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program,* p. 3.

fusion goal. Since the negotiations that will define the U.S. commitment to ITER are not complete, it is difficult to be precise now about the scale and distribution of the program elements. Nevertheless, some general principles are clear. They are presented below to define the structure of a fusion program including a burning plasma facility.

Present Structure

When considering the distribution, or balance, of activities in the fusion research program, it is instructive first to examine the program's present structure, which was defined by its restructuring into a science-based program in the mid-1990s. The goal of the U.S. fusion program is to develop the scientific and technological knowledge base for practical fusion energy production. This goal was formally enunciated in the program's mission statement: "Advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source."[16] The program has defined three goals to achieve in pursuit of this mission: "(1) Advance plasma science in pursuit of national science and technology goals; (2) Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and (3) Pursue fusion energy science and technology as a partner in the international effort."[17]

Pursuing all three of these goals supports the development of the knowledge base for an attractive energy source and has effectively defined a balanced fusion program. The third element of the program encompasses participation in international burning plasma experiments, an element that was considerably deemphasized upon the withdrawal of the United States in 1998 from the original ITER program. The first two elements include most current research activities on non-burning-plasma issues—such as plasma stability, nonlinear turbulence, self-organizing systems, magnetic field symmetry, and plasma sustainability at high pressure—carried out through the study of plasma behavior across a portfolio of advanced tokamak and non-tokamak confinement considerations. The activities range from relatively large national experiments on advanced tokamak and the related spherical torus configuration, to small, university-scale experiments studying a range of non-tokamak confinement concepts. The larger facilities, which are

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[16] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

[17] U.S. Department of Energy, *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, DOE/ER-0684, Washington, D.C., August 1996, p. 3.

well diagnosed, pursue simultaneous studies of a wide range of fusion science topics in near-reactor conditions; the smaller devices are typically focused on a specific topic, which can be addressed in detail with less overall capability and diagnostic coverage. This program rests on a foundation of research in theory and simulation, advanced diagnostic development, and enabling technology developments.

Given the program's budgetary constraints and the 1998 withdrawal of the United States from the original ITER consortium, several reviews—both internal[18] and external[19]—endorsed this program structure and strategy.

A few additional characteristics of the present program structure should be mentioned. With the restructuring to a science-based program in the mid-1990s and the subsequent U.S. withdrawal from the original ITER program, the technology programs in the U.S. fusion community shrank considerably. What remained of technology efforts was directed to supporting enabling technology for existing experimental programs—a Next Step Options design effort that led to the FIRE design—and relatively modest efforts at reactor-system design evaluations and some reactor-chamber research.

A second trait of the present program is that some separation exists between the university fusion research community and the larger national laboratory efforts. There are, of course, very productive collaborations between selected groups or individuals from universities and the large laboratory programs. Nevertheless, the bulk of activity in the universities is centered on research in smaller facilities constructed under the DOE Innovative Confinement Concepts program and located on campuses. The larger facilities at the national laboratories generally pursue research activities that are carried out as directed programs staffed mainly by laboratory staff and full-time, on-site collaborators from other laboratories and universities.

Required Elements of a Balanced Program

Recognizing the need to optimize the scientific output of all elements of the present U.S. fusion program, the distribution of activities among the elements of

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[18] R. Bangerter, G. Navratil, and N. Sauthoff, *2002 Fusion Summer Study Report*, 2003, available online at http://www.pppl.gov/snowmass_2002/snowmass02_report.pdf; Fusion Energy Sciences Advisory Committee, *A Restructured Fusion Energy Sciences Program*, Washington, D.C.: U.S. Department of Energy, 1996, available online at http://wwwofe.er.doe.gov/more_html/PDFFiles/FEACREPORT.pdf, accessed September 1, 2003.

[19] Secretary of Energy Advisory Board, *Realizing the Promise of Fusion Energy,* Task Force on Fusion Energy, Washington, D.C.: U.S. Department of Energy, 1999. Available online at http://www.fusionscience.org/FETfinal.pdf. Accessed September 1, 2003.

the program must be substantively reconfigured with a commitment to a burning plasma experiment. This rebalancing is especially required because finite funding resources cannot be expected to support all possible interests of the fusion community. A newly restructured program may be considered an evolutionary change from the program as currently structured, but changes will nonetheless be required across the whole fusion program.

One urgently needed change in the fusion community is the recognition, and the integration into program planning, of the strong interconnection among all elements of the expanded program. The often-cited distinction between an existing "base program" and a separate burning plasma program impedes the development of a unified rationale for the required broad-based program and undermines the support for the constituent parts of the program. As the burning plasma elements move forward, they will be necessarily integral parts of a balanced overall program. The distinction between a base program separate from the burning plasma activity, and vice versa, is no longer relevant or useful. Decisions on programmatic priority should be guided by the goal of optimizing the scientific output of the entire program, with due recognition for other program needs, such as workforce development.

The committee agrees that the rationale for a vigorous and broad program of research with both a burning plasma element and a domestic program of fusion science centered on understanding and concept optimization is compelling. However, this rationale must be dynamic, flexible, continuously developed, and enunciated clearly in order to maintain support.

The issue, then, is how to strike the relative balance of activities across a tightly integrated program that addresses, as much as possible, all of the critical fusion science issues. As the balance is clearly influenced by available funding, conditions could lead to the suppression of activity in one area or another, which occurred when the pursuit of a burning plasma experiment was halted in the late 1990s.

As the U.S. fusion community enters into the burning plasma era, the scale of the burning plasma experiment sets a new scale for other activities. In this respect, all other facilities—even in the largest national domestic programs—become smaller-scale focused (or "niche") programs that are designed to explore issues complementary to those in the centerpiece burning plasma program. This change continues the evolution of the fusion program to a smaller number of larger-scale experiments—but experiments that are still small compared with the single burning plasma facility—both on the national and international scales. This shift to "bigger science" has implications for all areas of the U.S. fusion community; they include the optimal role of universities and laboratories, the setting of priorities, the role of technology, and so on.

While a large portion of the program efforts will focus directly on the burning plasma experiment as centerpiece of the program, the actual level of effort in that area is dependent on the U.S. role in the ITER program. The pace of the ITER program will be decided by the international participants. The U.S. component of that program will be settled as the negotiations proceed. A U.S. role in producing high-technology components is important, however, because of the need to keep the domestic fusion science and technology program involved in the compelling science questions. Those negotiations will determine the U.S. budget contribution to ITER construction; it is important to allocate sufficient engineering resources to support the ITER negotiations.

Vigorous programs of experiments on existing facilities, theory, and computer simulation have brought the U.S. fusion program to the present level of understanding of the confinement of high-temperature plasma and readiness to pursue a burning plasma study. There is much to learn through a continuing experimental program that will directly impact ITER's performance. Major existing tokamaks and a new Korean machine[20] will be the workhorses of the program during ITER construction. Such experiments not only contribute to a deeper understanding of plasma physics, but also allow the testing of advanced diagnostic instrumentation that will be necessary for ITER itself. Some particular issues that these smaller tokamak experiments and theory can address in support of a burning plasma experiment were discussed earlier in this chapter (see the section entitled "Research Opportunities and Science and Technology Goals for the Domestic Fusion Program"). All of these facilities are useful now, and a subset should be kept running at least until ITER operates successfully.

The second major component of the U.S. fusion program is the investigation of fusion science issues on innovative magnetic configurations (other than the standard tokamak) to improve future fusion systems. The research goals and opportunities of this program, as summarized in the previous major section of this chapter, represent a reasonable level of effort for this component of the program. The investigations of these toroidal configurations require sufficient supporting programs in theory, diagnostic development, and enabling technologies. The composition of this portfolio will necessarily evolve over time, reflecting the completion of specific campaigns and the generation of new ideas for furthering the exploration of fusion science and improving confinement configurations.

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[20] The Korean Superconducting Tokamak Reactor (KSTAR) project is a long-pulse, superconducting tokamak being designed to explore advanced tokamak regimes under steady-state conditions. A team of U.S. national laboratories, universities, and industrial participants (including the Massachusetts Institute of Technology, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Princeton Plasma Physics Laboratory, and General Atomics) is supporting the Korean National Fusion Program in the design of KSTAR.

As is evident from the discussion here and in Chapter 2 of the compelling basic plasma physics questions that remain to be addressed, and because of the need to continually maintain a plasma-physics-literate workforce, another element of the restructured program will need to be the continued support for stewardship of the field of basic plasma science. Although this effort commands a relatively small fraction of the actual resources in the U.S. fusion program, it is a critical component of any U.S. fusion program structure. Finally, the program requires a fusion technology component, the scale of which is commensurate with the level of commitment and timing required to achieve the fusion energy goal. However, the technology programs at the present time will be those focused on enabling a successful burning plasma experiment—that is, focused primarily on those technologies important for the development of ITER.

The endorsement of the merits of these varied activities in the U.S. fusion program by this committee does not mean that every activity can or even should be supported unconditionally. Under any funding scenario that can be reasonably expected, decisions will need to be made regarding the relative priority of activities to pursue at any given time. Since the fusion program is a science-based program, these priorities need to be based on a discussion of scientific opportunities and goals. The need for setting priorities is discussed in the section below, "Setting Priorities to Strike the Balance."

Integration of Program Activities

The need to pursue the broad range of activities in the program as described above requires the participation of the entire fusion research community. As the program progresses inevitably to larger and more expensive facilities to access fusion-grade plasma parameters and phenomena, the need to integrate the research community into large-scale collaborative teams will grow. The community will be challenged by an increasing concentration on large facilities, similar to the situation in many other areas of physical science research. The entry into the ITER program is the most obvious evidence of this trend, but it holds true also for the present and future domestic program activities.

The guiding principle in preparing for participation in the ITER program is the need to position the U.S. fusion community to optimize the scientific output of its activities in the burning plasma program. This need has been addressed thus far in this report by recommending a technical level of participation. It is just as important for participation in the ITER program, and indeed for the entire U.S. fusion program, that the community consider fundamental changes in the way it operates in order to position itself to provide the intellectual leadership of chosen areas of research and to optimize the return on its investment.

It is reasonable to assume that the assignation of operating time to particular experiments on ITER will be determined in large part by the scientific merit of particular proposals. To optimize the position of the U.S. community in such an environment, teams of researchers need to be organized. These teams, composed of researchers from all parts of the community, should be focused on particular topical areas of high scientific interest. Organizing these teams quickly would help inform the U.S. negotiators about desired participation areas and would facilitate preparations for U.S.-team-based research at ITER. These collaborative teams would concentrate national expertise, positioning it to scientifically lead and effectively pursue chosen areas of research in the ITER program. The choice of major research thrusts will need to be determined by the community itself. Some examples may include elements of advanced tokamak development, stabilization of large-scale MHD instabilities, turbulence and transport studies, and so on. This approach requires the organization of the community around campaigns that are based more on scientific issues than on the operation of individual facilities. Such an approach appears to be working well in the European program for the operation of the Joint European Torus.

Another important element of this approach is to employ the technological means and to develop the sociological infrastructure for participation in large-scale programs by a dispersed community of researchers. Remote communications should be exploited to allow remote access to all data, real-time participation in experiments from remote sites, and active, real-time communication for joint planning, scientific interactions, and so on.

This transition to collaborative research based on scientific issues, coupled with a strong commitment to remote interactions, is a model required for the entire U.S. fusion program as it moves forward. Organizing the research efforts on the larger domestic facilities—the advanced tokamaks, spherical torus, stellarator, and reversed-field pinch—in a similar manner will support the transformation of the community to more of a user-group model and will more effectively engage the research community in those efforts. It will provide opportunities to engage the universities in the critical research topics of the program, strengthening them and the entire U.S. fusion effort and better coupling the fusion science program to the physical science and technology communities. In order for this approach to be effective, the large domestic facilities will need to support collaborative teaming through the shared governance of the research programs and planning.

While the nature of fusion science research has its unique features, the community can profitably learn how to coordinate dispersed national and international collaborations from other areas of "big science," such as the high-energy and astrophysics communities. Such coordination and collaboration will both optimize the large investments needed in the domestic program and give practical experience for participation in the ITER program.

The transformation of the culture of the program described here will take time, and it could even be somewhat demographically driven so as to minimize disruption. However, it is important to start making this transformation now so that a vibrant domestic research program with a sufficient workforce for fusion-grade facilities is available, and the community is intellectually and sociologically positioned to optimize its participation in ITER as well as to optimally exploit its domestic facilities.

SETTING PRIORITIES TO STRIKE THE BALANCE

The elements and thrusts of the U.S. fusion program are complementary and intertwined. However, a constrained federal budget environment is likely to continue during the period of implementation of ITER, and arguably this will be the greatest influence on the building of a balanced U.S. fusion program that includes participation in the ITER effort. Notwithstanding the success of the current portfolio approach to the U.S. fusion program, the budget stress facing the program is real and ongoing. The investment in ITER will be significant and must be accounted for in pursuit of a balanced U.S. fusion program. The OFES and the fusion community will have to make serious judgments with respect to priorities in determining its activities at all stages of the fusion program.

To ensure the continued success and leadership of the U.S. fusion program, the content, scope, and level of U.S. activity in fusion should be defined through a prioritized balancing of the program. This is especially true in the present context of expected lean budgets. Subsequent to a decision to construct and participate in a burning plasma experiment, the DOE should initiate a rigorous evaluation of the program priorities. This priority-setting process should be guided by the stated objective of maintaining a balanced program and a focus on fusion science, as discussed in this report.

The committee concludes that in order to develop a balanced program that will maximize the yield from participation in a burning plasma project, the prioritization process should be organized with three program objectives in mind:

- Advance plasma science in pursuit of national science and technology goals;
- Develop fusion science, technology, and plasma-confinement innovations as the central theme of the domestic program; and
- Pursue fusion energy science and technology as a partner in the international effort.

Through the prioritization process, the fusion community should identify and prioritize the critical scientific and technology questions to address in concentrated, extended campaigns, similar to the planning done for other areas of science such as for high-energy physics. A prioritized listing of those campaigns, with a clear and developed rationale for their importance, would be very helpful in generating support for their pursuit, while also developing a clear decision-making process in the fusion research community.

The types of questions that could be used to guide the prioritization process would include these:

1. What is the priority of current programs relative to the emerging requirements associated with participation in the ITER effort?
2. What is the future for U.S. tokamak research programs? What are the relative priorities of these programs?
3. What should be the scope, pace, and composition of the investigations regarding alternative and innovative configurations? Which approaches should have high priority?
4. What educational priorities should be set, and how should the presence of fusion science in academe be expanded?
5. How should the U.S. fusion program be linked to current and planned international fusion research programs?
6. What will be the impact of closing selected existing U.S. facilities to enable new research thrusts? What would be an appropriate transition strategy?

The prioritization process could follow the model of the budget planning and prioritization process used by the DOE High Energy Physics Advisory Panel. This panel's process has provided important input to DOE during the transitioning of ongoing research programs and facilities as new initiatives are implemented. The implementation of such a process will go a long way toward ensuring the best balance of the U.S. fusion program and its continued vitality and leadership.

Finally, while the U.S. fusion program is currently planning on integrating its burning plasma activity into the international fusion program, the committee notes that a reasonably high level of international cooperation is already in place—through formal planning activities, regular workshops, and some personnel exchanges for the four largest programs in the United States. The global fusion effort is moving toward a deepening of the international effort with the realization of the ITER project. Any future development of larger domestic experiments, and any definition of future program needs, will be driven by the parallel evolution of related activities in the international community. The international coordination of large science efforts can avoid duplication and exploit opportunities to perform leading-edge research on the best facilities in a cost-effective manner. It is thus important that consideration be given to coordinating all non-ITER-related activities discussed here with the global fusion program, as appropriate.

Appendixes

A

Charge to the Burning Plasma Assessment Committee

The committee will carry out an assessment of a program of burning plasma experiments and its role in magnetic fusion research. The study will have three components:

1. An assessment of the importance of a burning plasma experimental program to (a) fusion energy sciences and technology and the development of fusion as an energy source, (b) plasma physics, and (c) science in general.
2. An assessment of scientific and technical readiness to undertake a burning plasma experimental program.
3. An independent review and assessment of the plan for the U.S. magnetic fusion burning plasma experimental program as developed by the Department of Energy through the FESAC and Snowmass processes. The committee will make recommendations on the program strategy aimed at maximizing the yield of scientific and technical understanding as the foundation for the future development of fusion as an energy source.

Criteria for judging experiments will include the prospects for (a) achieving technical objectives, (b) extracting scientific and technological understanding and making progress of broad and generic applicability, and (c) contributing to the next steps in the experimental program.

An interim report will address the importance of the science and the readiness to undertake a burning plasma experiment. It will provide interim advice to the

Department of Energy regarding reentering negotiations to be a participant in a multinational burning plasma experiment (ITER).

The committee is not asked to evaluate fusion as an energy option. The committee will discuss and analyze the budget implications of its recommendations on program strategy but will not make budget recommendations per se.

B

Committee Meeting Agendas

FIRST MEETING
SEPTEMBER 17-18, 2002—WASHINGTON, D.C.

Tuesday, September 17

Closed Session

8:00 a.m.	Committee Business	

Open Session

1:30 p.m.	Welcome and Introductions	John Ahearne, Co-chair Raymond Fonck, Co-chair
1:45	Office of Fusion Energy Sciences (OFES) Perspective	Anne Davies, DOE/OFES
2:30	Office of Science and Technology Policy (OSTP) Perspective	J. Patrick Looney, OSTP
3:15	Break	

3:30	DOE Perspectives	Raymond Orbach, DOE
4:15	Open Discussion	Ahearne, Fonck
5:00	Adjourn	

Wednesday, September 18

Closed Session

8:00 a.m.	Committee Business	

Open Session

9:00	International Thermonuclear Experimental Reactor (ITER) Presentation	Karl Lackner, European Fusion Development Agreement
10:05	Fusion Ignition Research Experiment (FIRE) Presentation	Dale Meade, Princeton Plasma Physics Laboratory (PPPL)
11:05	Break	
11:30	Snowmass Outcomes	Gerald Navratil, Columbia University; Ned Sauthoff, PPPL
12:30 p.m.	Lunch	
1:30	Report on Fusion Energy Sciences Advisory Committee (FESAC) Action	Stewart Prager, University of Wisconsin
2:30	The "Science First" Approach	Bruno Coppi, Massachusetts Institute of Technology
3:30	Break	
3:45	Open Discussion	Ahearne, Fonck
4:45	Adjourn	

Closed Session

5:00	Committee Business
6:30	Adjourn

SECOND MEETING
NOVEMBER 17-18, 2002—WASHINGTON, D.C.

Monday, November 18

Closed Session

8:30 a.m.	Committee Business

Open Session

9:00	Fusion Power: I Think We're Lost	Robert Hirsch, Chair, BEES
9:45	Q&A on DOE/OFES Program ITER Q&A Session	Anne Davies, DOE/OFES Ned Sauthoff, PPPL
11:00	OSTP Perspective	John Marburger, OSTP
11:30	Break	
11:40	ITER Q&A Session (cont'd)	Ned Sauthoff, PPPL
12:10 p.m.	Lunch	
1:15	Comments by Telephone	Marshall Rosenbluth, University of California at San Diego

Closed Session

1:45	Committee Business
5:30	Adjourn

Tuesday, November 19

Closed Session

8:00 a.m.	Committee Business
1:00 p.m.	Adjourn

THIRD MEETING
JANUARY 17-18, 2003—LA JOLLA, CALIFORNIA

Friday, January 17

Closed Session

12:45 p.m.	Committee Business

Open Session

2:30	Comments by Telephone	Anne Davies, DOE/OFES
2:45	Additional Elements of FESAC Plan	Stewart Prager, University of Wisconsin
3:30	Break	
3:45	Fusion Power	Stephen Dean, Fusion Power Associates
4:30	Goldston FESAC Report (Q&A)	Robert Goldston, PPPL
5:45	Adjourn	

Saturday, January 18

Closed Session

8:15 a.m.	Committee Business

Open Session

9:00	Review of U.S. Programs and Processes	Michael Mauel, Columbia University
10:00	Break	
10:30	Future of Tokamak Facilities with a Burning Plasma Experiment	Ronald Stambaugh, General Atomics
11:30	Multimachine Strategy	Gerald Navratil, Columbia University
12:30 p.m.	Lunch	

Closed Session

1:15	Committee Business
5:30	Adjourn

Sunday, January 19

Closed Session

8:30 a.m.	Committee Business
12:00 p.m.	Adjourn

FOURTH MEETING
MAY 5-6, 2003—WASHINGTON, D.C.

Monday, May 5

Closed Session

8:30 a.m.	Committee Business

Open Session

11:00	DOE/OFES Program Plan	Anne Davies, OFES/DOE
11:45	OSTP Perspective	J. Patrick Looney, OSTP
12:00 p.m.	Lunch	

Closed Session

1:00	Committee Business
5:30	Adjourn

Tuesday, May 6

Closed Session

8:00 a.m.	Committee Business
12:00 p.m.	Lunch
1:00	Committee Business
5:00	Adjourn

C

Proposed Burning Plasma Experiments

As detailed in the DOE Fusion Energy Sciences Advisory Committee report *A Burning Plasma Program Strategy to Advance Fusion Energy* and discussed in other reports,[1] three burning plasma experiments have been proposed—the International Thermonuclear Experimental Reactor (ITER), the Fusion Ignition Research Experiment (FIRE), and the Italian IGNITOR experiment. These three experiments range from a reactor-scale device using superconducting magnets, to compact, high-field copper-magnet devices. While each of the three devices is capable of addressing fusion physics and technology issues to some extent, they vary markedly in their missions, schedules, and budgets.

INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR

ITER is an international facility that is designed to demonstrate the scientific feasibility of fusion as an energy source. It will also develop and test key features of

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[1] Fusion Energy Sciences 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; Proceedings of the 1999 Snowmass Fusion Summer Study, available online at http://www.ap.columbia.edu/SMproceedings/; Snowmass 2002 Fusion Summer Study, Executive Summary, available online at http://web.gat.com/snowmass/exec-summary.pdf.

TABLE C.1 Parameters for Burning Plasmas in the International Thermonuclear Experimental Reactor (ITER)

Quantity	Value
Major radius	6.2 m
Minor radius	2.0 m
Magnetic field	5.3 T
Plasma current	15 MA
Fusion power	500 MW
Q (fusion power/power in)	≥10
Burn time	≥400 s
Wall loading	0.57 MW/m^2
Plasma volume	837 m^3
Heating/current drive power	73 MW

SOURCE: Information obtained from the ITER Web site, http://www.iter.org/. Accessed September 1, 2003.

the technology that will be required for a fusion power plant. A cutaway figure of the device is shown in Figure 1.1 in Chapter 1 of this report, and the ITER operating parameters are summarized in Table C.1. ITER is a $5 billion device that utilizes reactor-relevant fusion technologies, including superconducting magnets and techniques for control of the plasma profiles, to create self-heated plasmas.

The ITER project has benefited greatly from the expertise and scrutiny of fusion-plasma researchers throughout the world. The present design is the result of a decade of effort. This work included one major redesign that reduced the anticipated cost by a factor of 2 by reducing the size and eliminating some of the capability to test fusion power components and technologies. The engineering design of ITER is well developed, and prototypes for many of the systems have been built. ITER has been designed to accommodate a range of heating and current drive technologies and to have the most complete set of plasma diagnostics of the three proposed burning plasma experiments. It will facilitate studies of plasmas for pulse lengths much longer than the plasma current redistribution time, which will enable studies of steady-state operation. The long pulse capability, the range and flexibility of heating and current drive technologies, and the extensive diagnostic set provide the capability to explore and evaluate advanced, steady-state operating regimes. The present ITER design would demonstrate the integrated operation of some of the important technologies for fusion power. It also has the capability to test some of the key nuclear components necessary for a fusion power plant, such as tritium breeding blanket modules required to close the deuterium-tritium (D-T) fuel cycle.

ITER provides excellent opportunities to address key physics issues. Of the three proposed burning plasma experiments, the relevant dimensionless physics parameters of ITER are closest to those expected for a fusion power plant. The operating regime of ITER facilitates the study of alpha-particle-driven instabilities at temperatures relevant to a power plant. The flexible plasma control capability and long pulse duration will permit the exploration of self-driven current regimes, permitting studies relevant to steady-state operation. Two phases of operation are planned for ITER. In the first phase, physics issues related to controlled burn will be evaluated. Assuming successful long pulse (up to 3,000 s), high-fusion-power operation, the second phase of the experiment will concentrate on the nuclear testing of materials components, although not at the flux and fluence levels required for a power plant.

All of the burning plasma experiments under consideration are based on the D-T reaction, chosen because of its large cross section and relatively low reaction temperature. There is sufficient tritium available for these experiments. However, tritium does not occur naturally, and so it must be bred in the fusion reactor itself to make fusion power a reality. This can be accomplished using the fusion-produced neutrons in a lithium-containing “blanket,” which surrounds the burning plasma. The second phase of ITER is planned to have the capability to address this important technology issue by testing prototype breeding blankets using the neutrons from an actual burning plasma.

Two challenges for ITER require further physics and technology research and development. One challenge involves the expected significant erosion of the divertor owing to repetitive oscillations of the plasma edge (edge-localized modes, or ELMs). The other issue is that the projected tritium retention in redeposited carbon has the potential to increase the machine downtime because of the need to remove the trapped tritium. These topics have been identified as high priorities for ongoing research. A more complete predictive understanding of the characteristics of the plasma edge in high-confinement regimes would reduce the uncertainty and increase confidence in the performance projections for ITER (as well as any other burning plasma experiment). Developing this understanding should also be a key element of the ongoing R&D program.

FUSION IGNITION RESEARCH EXPERIMENT

FIRE is a U.S. design study in the advanced preconceptual phase. Preliminary estimates indicate a cost of approximately $1.3 billion for this device, not including diagnostics. FIRE is intended as a major next step in magnetic fusion research. The mission of FIRE is to attain, explore, and optimize magnetically confined, fusion-dominated plasmas in order to provide the physics knowledge base for the design of a fusion reactor. The FIRE option involves somewhat smaller extrapolations in physics and technology than those required for ITER and defers the integration of the fusion physics and technology to later experiments. The design is based on cryogenically cooled copper magnets, with a relatively high magnetic field and modest size as compared, for example, with ITER. FIRE employs strong plasma shaping and internal feedback control coils, both of which improve the capability to operate at high "beta" (i.e., plasma pressure normalized by the confining magnetic field) and at a relatively large fraction of internally generated (i.e., bootstrap) current. FIRE can operate at pulse lengths up to a couple of current redistribution times.

The FIRE design facilitates the achievement of self-consistent, near-steady-state operation with large self-driven currents. However, in the present design, the plasma heating and current drive needed to achieve and control these discharges are limited. A key element of an ongoing R&D program for FIRE will be the development of electrical insulators for the magnets that are less susceptible to neutron damage. While the number of full-power D-T pulses will be sufficient for the investigation of burning plasma physics, if current materials are used, the useful life of the device will be limited by neutron damage. As in the case of ITER, divertor deterioration from plasma edge oscillations (ELMs) is an important issue that will benefit from further R&D.

While FIRE is a technically sound design as presently proposed, it is a U.S.-centered project and hence does not benefit from the cost sharing and additional expertise that can be gained by international cooperation. FIRE would cost the United States as much as its participation in ITER but would pursue a more limited scientific mission and offer less in the development of new fusion technology. The FIRE design should thus be viewed as a contingency to be revisited, among several concepts, if the ITER project does not proceed.

The attractiveness of the tokamak as a practical energy source would be increased significantly if it could be operated in steady-state and high-performance regimes. Thus, the ability of a burning plasma experiment to explore such advanced tokamak (AT) operating regimes is highly desirable. Important factors include the flexibility to effect strong plasma shaping, plasma profile control, active magnetohydrodynamic (MHD) control, long pulses, and detailed profile measurements. Both FIRE and ITER have significant AT capabilities and plans to study aspects of these regimes. If successful in ITER, for example, these operating modes would be used for the second phase of ITER operation, in which long pulses and high neutron fluence are required. FIRE can explore AT regimes with strong plasma shaping and active MHD control, which are both advantageous features in producing high self-driven currents and high performance. ITER can explore high self-driven current regimes with a flexible array of heating, current drive, and rotational drive systems, with good profile measurements.

THE IGNITOR EXPERIMENT

IGNITOR, an Italian project, is a compact, cryogenically cooled, copper-magnet device capable of operation at high magnetic field. It is designed to achieve ignition in D-T plasmas and to study alpha-particle confinement and the heating and control of ignited plasmas. While potentially cost-effective in achieving the burning plasma regime, the resulting plasma conditions and flexibility of the device are more limited in the reactor-relevant physics that can be addressed. The IGNITOR design also raises a number of concerns, including less well established performance projections, questions about whether the required peak pressure profiles can be realized, and issues surrounding the structural integrity of the vessel.[2]

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[2] R. Bangerter, G. Navratil, and N. Sauthoff, 2002 Fusion Summer Study Report, 2003, pp. 5, 66-67, 69. Available online at http://www.pppl.gov/snowmass_2002/snowmass02_report.pdf. Accessed September 1, 2003.

D

Fusion Community Recommendations

The fusion community has been involved in many assessments of the best path for fusion science as it moves toward developing fusion as an energy source. Most recently these assessments have involved the publication of the DOE Fusion Energy Sciences Advisory Committee (FESAC) *Review of Burning Plasma Physics* (September 2001); the convening of a community workshop in Snowmass, Colorado (July 2002); the commissioning of a FESAC report, *A Burning Plasma Program Strategy to Advance Fusion Energy* (September 2002); and another FESAC report, *A Plan for the Development of Fusion Energy* (March 2003). The most prescient elements and recommendations of these efforts are presented in this appendix as summaries prepared by the committee, with excerpts from the respective reports as appropriate.

FREIDBERG REPORT

In October 2000, FESAC was charged with carrying out a review of burning plasma physics. Reporting in September 2001, the FESAC panel led by Jeffrey Freidberg of the Massachusetts Institute of Technology produced a report with five recommendations.[1] The panel concluded that "NOW is the time for the U.S. Fusion Energy

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[1] Fusion Energy Sciences Advisory Committee, *Review of the Burning Plasma Physics*, DOE/SC-0041. Washington, D.C.: U.S. Department of Energy, 2001 (hereafter referred to as FESAC, *Review of the Burning Plasma Physics*).

Sciences Program to take the steps leading to the expeditious construction of a burning plasma experiment" and that "funds for a burning plasma experiment should arise as an addition to the base Fusion Energy Sciences budget."[2] The report suggested that the program should establish what the panel called "a proactive U.S. plan on burning plasma experiments."[3] To that end, the report said, a workshop should be held for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the report said, the workshop "should determine which of the specific burning plasma options are technically viable but should not select among them" and "confirm that a critical mass of fusion scientists believe that the time to proceed is now and not some undefined time in the future."[4] The panel also suggested that the DOE charge FESAC with the mission of forming an "action" panel to select among the technically viable burning plasma experimental options and initiate a review by a National Research Council panel with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by the fall of 2003.

In summary, the panel believed that "understanding burning plasmas would be an immense physics accomplishment of wide scientific significance and would be a huge step toward the development of fusion energy."[5] The panel suggested a course of action that it believed would enable the presentation of an optimal burning plasma experimental plan to the nation no later than July 2004.

SNOWMASS WORKSHOP

Following the FESAC plan, a fusion summer study was organized in Snowmass, Colorado, to take place July 8-19, 2002. The study carried out a critical assessment of major next steps in the fusion energy sciences program in both magnetic fusion energy (MFE) and inertial fusion energy (IFE). The resulting report describes the summer study and its outcomes:

> The conclusions of this study were based on analysis led by over 60 conveners working with hundreds of members of the fusion energy sciences community extending over 8 months. This effort culminated in two weeks of intense discussion by over 250 U.S. and 30 foreign fusion physicists and engineers. The objectives of the Fusion Summer Study were three-fold:

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[2] FESAC, *Review of the Burning Plasma Physics*, pp. 11-12.

[3] FESAC, *Review of the Burning Plasma Physics*, p. 12.

[4] FESAC, *Review of the Burning Plasma Physics*, p. 12.

[5] FESAC, *Review of the Burning Plasma Physics*, p. 14.

- Review the scientific issues in burning plasmas, address the relation of burning plasma in tokamaks to innovative MFE confinement concepts, and address the relation of ignition in IFE to integrated research facilities.
- Provide a forum for critical discussion and review of proposed MFE burning plasma experiments (IGNITOR, FIRE, and ITER) and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas.
- Provide a forum for the IFE community to present plans for prospective integrated research facilities, assess the present status of the technical base for each, and establish a timetable and technical progress necessary to proceed for each.[6]

Here, only the elements of the workshop dealing with MFE are considered. At the end of the 2 weeks the participants completed their task and reached consensus on a set of five conclusions:

1. The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science. The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research.
2. The three experiments proposed [ITER, FIRE, and IGNITOR] to achieve burning plasma operation range from compact, high field, copper magnet devices to a reactor-scale superconducting-magnet device. These approaches address a spectrum of both physics and fusion technology, and vary widely in overall mission, schedule and cost.
3. IGNITOR, FIRE, and ITER would enable studies of the physics of burning plasma, advance fusion technology, and contribute to the development of fusion energy. The contributions of the three approaches would differ considerably.

    - IGNITOR offers an opportunity for the early study of burning plasmas aiming at ignition for about one current redistribution period.
    - FIRE offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations under quasi-stationary conditions (several current redistribution time periods) and would contribute to plasma technology.
    - ITER offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations for long durations (many current redistribution time periods) with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology.

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[6] R. Bangerter, G. Navratil, and N. Sauthoff, *2002 Fusion Summer Study Report*, 2003, available online at http://www.pppl.gov/snowmass_2002/snowmass02_report.pdf, p. 2. Accessed September 1, 2003.

4. There are no outstanding engineering-feasibility issues to prevent the successful design and fabrication of any of the three options. However, the three approaches are at different levels of design and R&D. There is confidence that ITER and FIRE will achieve burning plasma performance in H-mode based on an extensive experimental database. IGNITOR would achieve similar performance if it either obtains H-mode confinement or an enhancement over the standard tokamak L-mode. However, the likelihood of achieving these enhancements remains an unresolved issue between the assessors and the IGNITOR team.
5. The development path to realize fusion power as a practical energy source includes four major scientific elements [see Figure D.1 in this appendix]:
   - Fundamental understanding of the underlying science and technology, and optimization of magnetic configurations
   - Plasma physics research in a burning plasma experiment
   - High performance, steady-state operation
   - Development of low-activation materials and fusion technologies.[7]

PRAGER REPORT

Following the Freidberg report's strategy, in February 2002 the DOE Office of Science's Acting Director, James Decker, charged FESAC to establish a high-level panel to recommend a strategy for burning plasma experiments. The 47-member panel, chaired by Stewart Prager of the University of Wisconsin at Madison, met in Austin, Texas, August 6-8, 2002, and its strategy recommendation report was adopted by FESAC on September 5, 2003.[8] The panel based its recommendations on the Snowmass assessment, with the aim of presenting a strategy to enable the United States to "proceed with this crucial next step in fusion energy science."[9] The report states:

> The strategy was constructed with awareness that the burning plasma program is only one major component in a comprehensive development plan for fusion energy. A strong core science and technology program focused on fundamental understanding, confinement configuration optimization, and the development of plasma and fusion technologies is essential to the realization of fusion energy. The core program will also be essential to the successful guidance and exploitation of the

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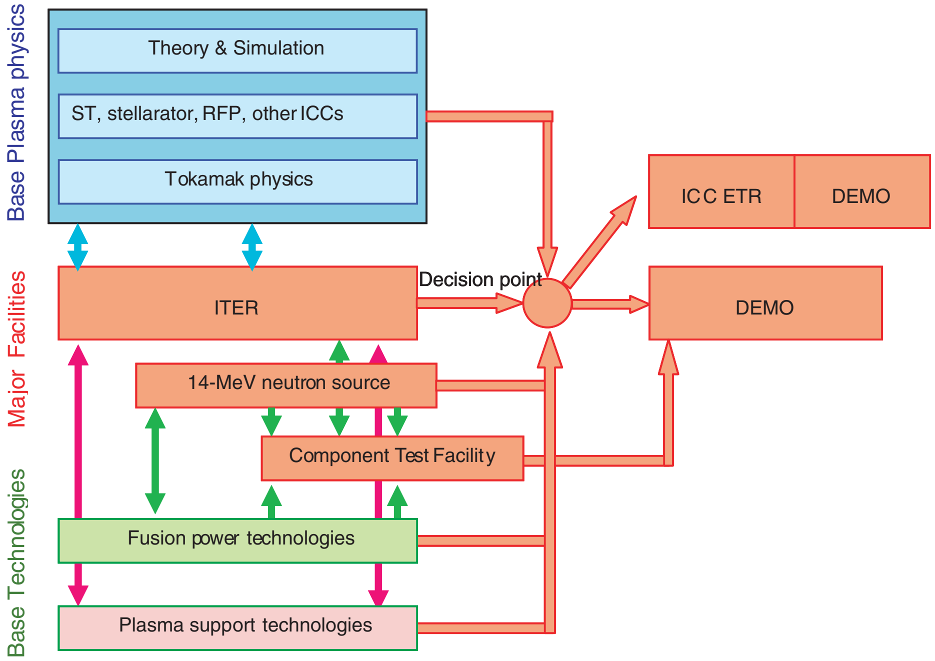
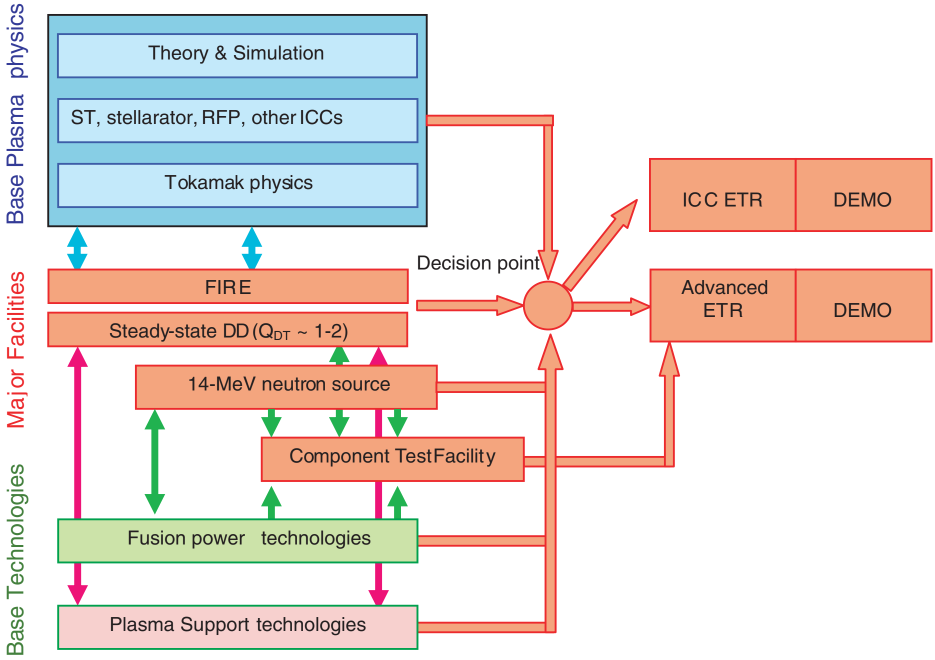
[7] R. Bangerter, G. Navratil, and N. Sauthoff, *2002 Fusion Summer Study Report*, 2003. Available online at http://www.pppl.gov/snowmass_2002/snowmass02_report.pdf, pp. 3-8. Accessed September 1, 2003.

[8] Fusion Energy Sciences Advisory Committee, *A Burning Plasma Program Strategy to Advance Fusion Energy*, Washington, D.C.: U.S. Department of Energy, 2002 (hereafter referred to as FESAC, *A Burning Plasma Program Strategy to Advance Fusion Energy*).

[9] FESAC, *A Burning Plasma Program Strategy to Advance Fusion Energy*, p. 3.


Base Plasma physics
Theory & Simulation
ST, stellarator, RFP, other ICCs
Tokamak physics
Major Facilities
ITER
Decision point
ICC ETR
DEMO
DEMO
14-MeV neutron source
Component Test Facility
Base Technologies
Fusion power technologies
Plasma support technologies


Base Plasma physics
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Tokamak physics
Major Facilities
FIRE
Steady-state DD (Q_{DT} ~ 1-2)
Decision point
ICC ETR
DEMO
Advanced ETR
DEMO
14-MeV neutron source
Component Test Facility
Base Technologies
Fusion power technologies
Plasma Support technologies

FIGURE D.1 Development paths for realizing fusion power as a practical energy source, as developed by the Snowmass 2002 Fusion Summer Study Workshop. NOTE: ST—spherical torus; RFP—reversed-field pinch; ICC—innovative confinement concepts; ETR—experimental test reactor; DEMO—demonstration fusion power plant; DD—deuterium-deuterium reactions. SOURCE: Snowmass 2002 Fusion Summer Study, available online at http://web.gat.com/snowmass/exec-summary.pdf. Courtesy of Snowmass 2002 Fusion Summer Study Workshop organizers.

> burning plasma program, providing the necessary knowledge base and scientific work force.[10]

The panel made two primary findings:

> - ITER and FIRE are each attractive options for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths.
> - Because additional steps are needed for the approval of construction of ITER or FIRE, a strategy that allows for the possibility of either burning plasma option is appropriate.[11]

With this background, the panel put forth the following strategy recommendations:

> - Since ITER is at an advanced stage, has the most comprehensive science and technology program, and is supported internationally, [the United States] should now seek to join the ITER negotiations with the aim of becoming a partner in the undertaking, with technical, programmatic and timing considerations as follows:
>
>   The desired role is that the U.S. participates as a partner in the full range of activities, including full participation in the governance of the project and the program. We anticipate that this level of effort will likely require additional funding of approximately $100M/yr.
>
>   The minimum acceptable role for the U.S. is at a level of effort that would allow the U.S. to propose and implement science experiments, to make contributions to the activities during the construction phase of the device, and to have access to experimental and engineering data equal to that of all partners.
>
>   The U.S. performs a cost analysis of U.S. participation and reviews the overall cost of the ITER project.

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[10] FESAC, *A Burning Plasma Program Strategy to Advance Fusion Energy*, p. 3.

[11] FESAC, *A Burning Plasma Program Strategy to Advance Fusion Energy*, p. 3.

> The Department of Energy concludes, by July, 2004, that ITER is highly likely to proceed to construction and terms have been negotiated that are acceptable to the U.S. Demonstrations of likelihood could include submission to the partner governments of an agreement on cost-sharing, selection of the site, and a plan for the ITER Legal Entity.
>
> - Since FIRE is at an advanced pre-conceptual design stage, and offers a broad scientific program, [it] should proceed to a physics validation review, as planned, and be prepared to initiate a conceptual design by the time of the U.S. decision on participation in ITER construction.
> - If ITER negotiations succeed and the project moves forward under terms acceptable to the U.S., then the U.S. should participate. The FIRE activity should then be terminated.
> - If ITER does not move forward, then FIRE should be advanced as a U.S.-based burning plasma experiment with strong encouragement of international participation.
> - If IGNITOR is constructed in Italy, then the U.S. should collaborate in the program by research participation and contributions of related equipment, as it does with other major international facilities.
> - A strong core science and technology program is essential to the success of the burning plasma effort, as well as the overall development of fusion energy. Hence, this core program should be increased in parallel with the burning plasma initiative.
> - A burning plasma science program should be initiated by the OFES with additional funding in FY04 sufficient to support this strategy.[12]

GOLDSTON REPORT

With the completion of the FESAC part of the Freidberg report's plan of action, and with the continuing work of this National Research Council committee, DOE charged FESAC to develop a plan for the deployment within 35 years of a fusion demonstration power plant, leading to the commercial application of fusion energy by midcentury. The plan was developed by a committee under the leadership of Robert Goldston of Princeton Plasma Physics Laboratory. It dealt with development paths for both MFE and IFE, although the present discussion focuses only on the MFE aspects of the report.

The Goldston report,[13] adopted by FESAC on March 5, 2003, goes well beyond the DOE plan for a magnetic fusion burning plasma experiment envisioned in the charge of the NRC's Burning Plasma Assessment Committee (BPAC), including the consideration of inertial fusion energy. Therefore, many aspects of the plan are

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[12] FESAC, *A Burning Plasma Program Strategy to Advance Fusion Energy*, pp. 3-4.

[13] Fusion Energy Sciences Advisory Committee, *A Plan for the Development of Fusion Energy*, Washington, D.C.: U.S. Department of Energy, 2003 (hereafter referred to as FESAC, *A Plan for the Development of Fusion Energy*).

not relevant to the charge before BPAC, although aspects of the MFE development plan as laid out in the Goldston panel report are relevant to this committee's work.

According to the Goldston report, key elements of its plan are as follows:

- To develop fusion energy on the 35-year timescale, it is "imperative to have a strong balanced program that develops fusion science and technology in parallel."[14]
- The report also says that "additional funding" is needed to "participate in the construction and utilization of ITER, or, if ITER does not advance to construction, to complete the design of and to construct the domestic FIRE experiment."[15]

Objectives selected from the report that are relevant to the implementation of a U.S. plan for a burning plasma experiment include these:

- From the present to 2009

  —Begin construction of ITER, and develop science and technology to support and utilize this facility. If ITER does not move forward to construction, then complete the design and begin construction of the domestic FIRE experiment.
  —Test fusion technologies in non-fusion facilities in preparation for early testing in ITER, including first blanket modules, and to support configuration optimization.[16]

- From 2009 to 2019

  —Demonstrate burning plasma performance in NIF and ITER (or FIRE).
  —Obtain plasma and fusion technology data for MFE CTF [Component Test Facility] design, including initial data from ITER test blanket modules.
  —Demonstrate efficient long-life operation of IFE and MFE systems, including liquid walls.[17]

The report finds that the U.S. fusion energy sciences program is still suffering from the budget cuts of the mid-1990s and the loss of what it terms "a clear national commitment to develop fusion energy,"[18] with concomitant increasing difficulty in retaining technical expertise in key areas. The Goldston plan also estimates that the fusion budget needs to double over the next 5 years to begin to implement the development path foreseen in the report.

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[14] FESAC, *A Plan for the Development of Fusion Energy*, p. 6.
[15] FESAC, *A Plan for the Development of Fusion Energy*, p. 6.
[16] FESAC, *A Plan for the Development of Fusion Energy*, p. 10.
[17] FESAC, *A Plan for the Development of Fusion Energy*, p. 11.
[18] FESAC, *A Plan for the Development of Fusion Energy*, p. 9.

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Committee's Interim Report

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

December 20, 2002

Dr. Raymond Orbach
Director, Office of Science
SC-1/Forrestal Building
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

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.

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[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.

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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

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[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

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[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 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

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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/>.

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

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-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.

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

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[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>

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

F

Fusion Reactor Concepts

Although the general scheme of confining a hot and dense plasma within a magnetic bottle is common to all magnetic fusion configurations, the different strategies are worth noting. In this appendix, the tokamak (see Figure F.1), the spherical torus and the spheromak (see Figure F.2), the stellarator (see Figure F.3), and the reversed-field pinch (see Figure F.4) configurations are discussed.

THE TOKAMAK CONFIGURATION

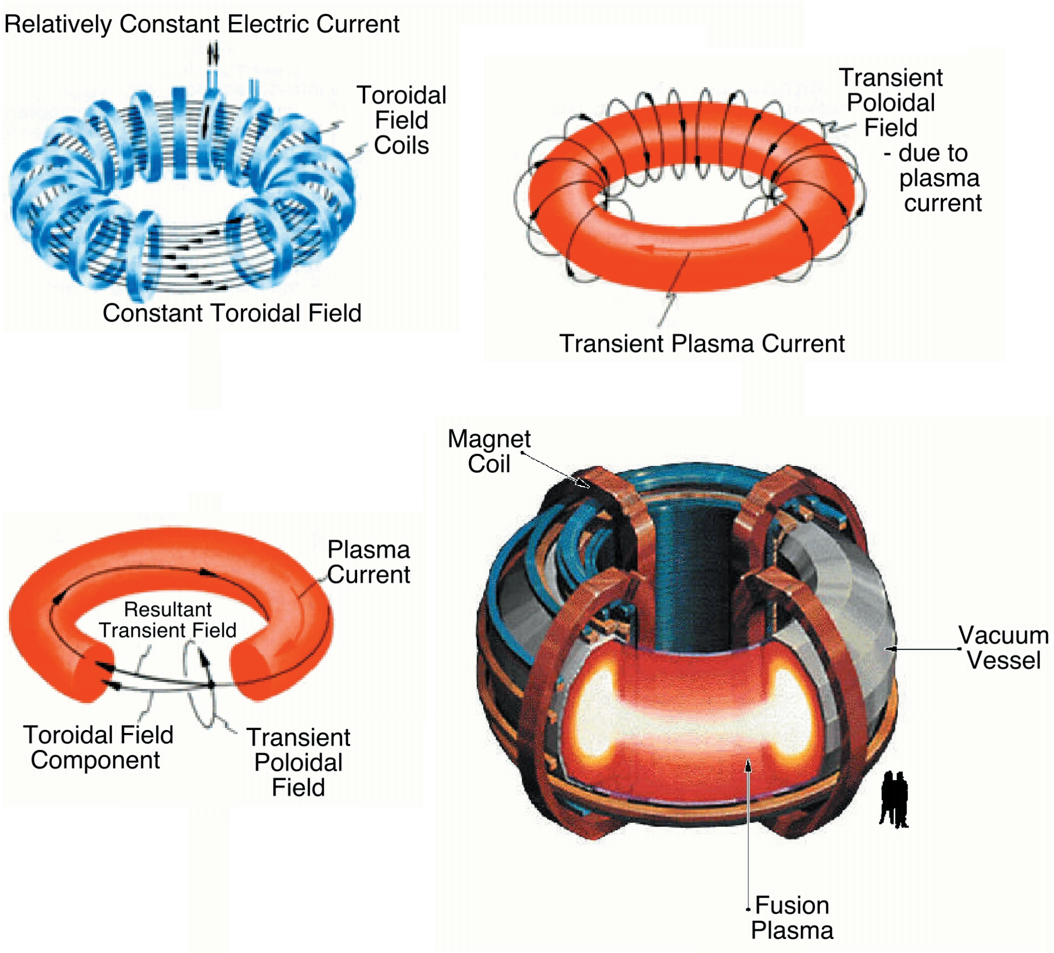
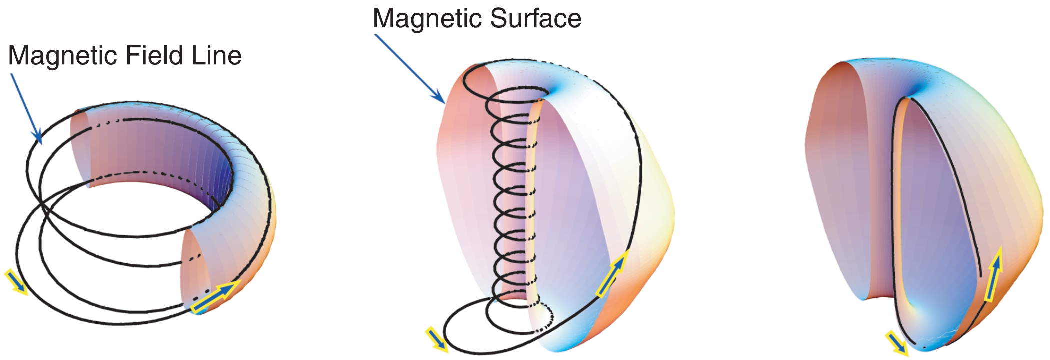


FIGURE F.1 The components of the tokamak confinement configuration, one of the more advanced plasma confinement concepts. It uses a strong toroidal field created by external field coils (top left) to stabilize the plasma while using a poloidal field created by a toroidal plasma current to confine the particles (upper right). The final configuration depends on the interaction of these fields (bottom left) and includes a large vacuum vessel to isolate the hot plasma from the surrounding environment (bottom right; people shown for scale). Courtesy of General Atomics and Princeton Plasma Physics Laboratory.

EXTENSIONS OF THE TOKAMAK— SPHERICAL TORUS AND SPHEROMAK



Tokamak Plasma
(safety factor q = 4)

Spherical Torus Plasma
(safety factor q = 12)

Spheromak Plasma
(safety factor q = 0.03)

FIGURE F.2 Examples of the magnetic topologies of three related toroidal configurations with increasing curvature and varying stability characteristics. The tokamak (left) uses a strong external toroidal field to provide robust stability against pressure- and current-driven instabilities. The spherical torus (center) uses a weak toroidal field in a compact configuration to allow access to higher β values than those obtained in the tokamak. The spheromak (right) uses internal plasma currents only to provide the confining poloidal field plus a weak toroidal field. A larger safety factor indicates a higher level of protection from current-driven instabilities. Courtesy of M. Peng, Princeton Plasma Physics Laboratory.

THE STELLARATOR

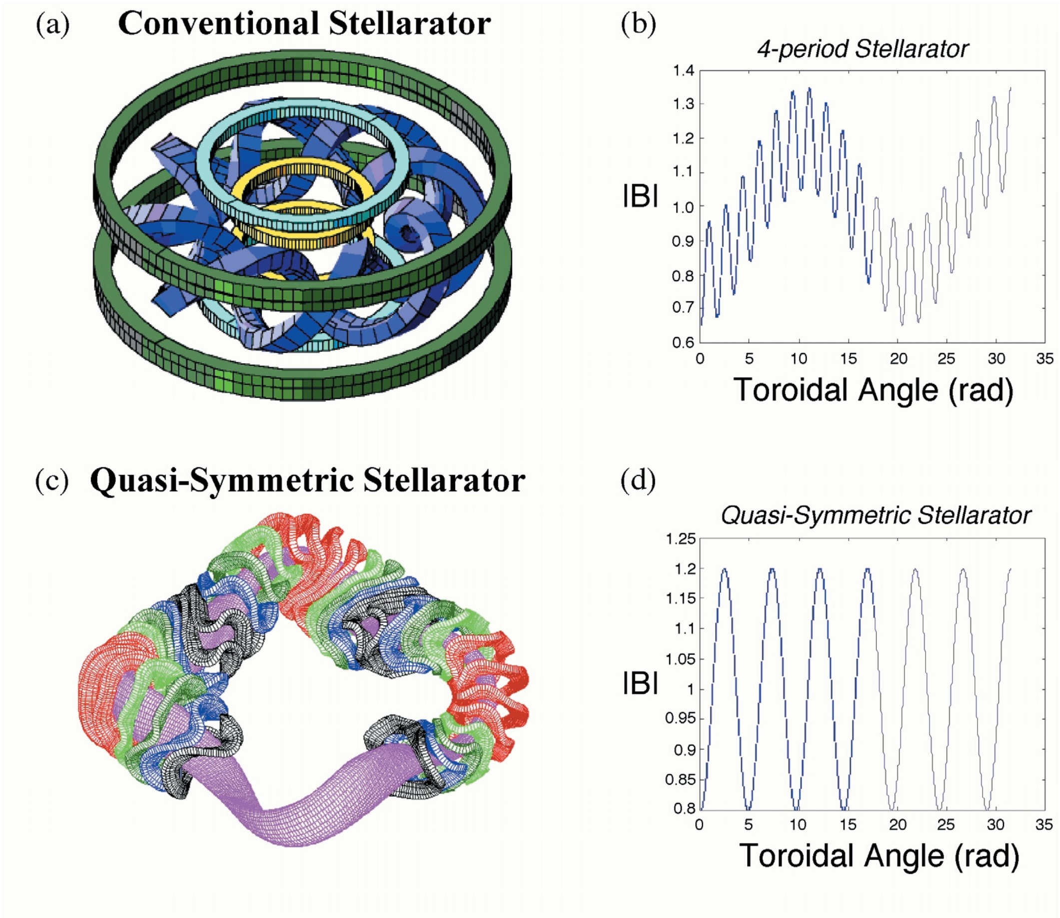


FIGURE F.3 The stellarator concept uses complex three-dimensional coil and magnetic-flux surfaces to create a quasi-symmetric configuration in which the magnetic field appears to be only two-dimensional in the frame of reference of a moving particle in the plasma. The conventional stellarator (a) has relatively simple helical symmetry and multiple harmonics in the field strength along a field line (b), which in turn gives rise to large particle losses. In contrast, the quasi-symmetric stellarator (c) eliminates the harmonics and produces a field line with single harmonic symmetry (d), effectively eliminating toroidal curvature (i.e., the long-period feature in (b)) and dramatically improving particle confinement. Courtesy of D.T. Anderson, University of Wisconsin at Madison.

THE REVERSED-FIELD PINCH

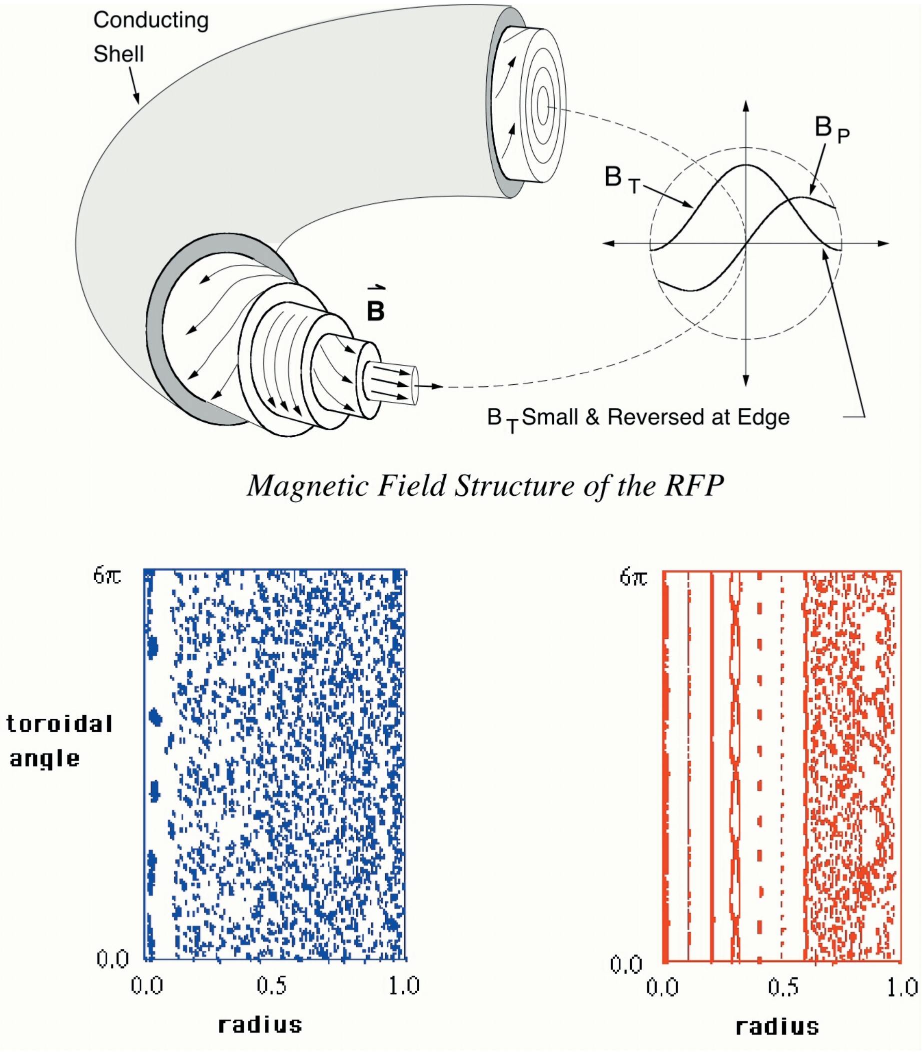


FIGURE F.4 A magnetic confinement concept such as the reversed-field pinch (RFP) (top) is a relatively self-organizing configuration that is subject to turbulent magnetic field structures. The magnetic topology includes a reversal of the toroidal field inside the plasma owing to plasma currents. Under normal inductive current drive, the magnetic field lines can readily become chaotic, as indicated by a puncture plot of the field lines as they traverse a poloidal plane (bottom left). With finer control of the plasma currents, well-defined flux surfaces are restored (bottom right). NOTE: B_T, toroidal magnetic field; B_P, poloidal magnetic field. Courtesy of S.C. Prager, University of Wisconsin at Madison.

G

Biographies of Committee Members

JOHN F. AHEARNE, *Co-chair*, is the director of the Ethics Program for Sigma Xi, the Scientific Research Society; a lecturer in public policy at Duke University; and an adjunct scholar at Resources for the Future. His professional interests are reactor safety, energy issues, resource allocation, and public policy management. He has served as commissioner and chair of the U.S. Nuclear Regulatory Commission, system analyst for the White House Energy Office, Deputy Assistant Secretary for Energy, and Principal Deputy Assistant Secretary for Defense. Dr. Ahearne currently serves on the Department of Energy's Nuclear Energy Research Advisory Committee and chairs the National Research Council's (NRC's) Board on Radioactive Waste Management. In addition, Dr. Ahearne has been active in several NRC committees examining issues in risk assessment. He is a fellow of the American Physical Society, Society for Risk Analysis, American Association for the Advancement of Science, American Academy of Arts and Sciences, and a member the American Nuclear Society and the National Academy of Engineering. Dr. Ahearne received his Ph.D. in physics from Princeton University.

RAYMOND FONCK, *Co-chair,* is a professor in the Department of Engineering Physics at the University of Wisconsin at Madison. He received his Ph.D. in physics from the University of Wisconsin in 1978. He was at the Princeton Plasma Physics Laboratory (PPPL) from 1978 through 1989; there he was deputy head of the Princeton Beta Experiment Modification Tokamak project and head of the spectroscopy group on the Tokamak Fusion Test Reactor experimental team. He joined the Department of Nuclear Engineering and Engineering Physics at Wisconsin in 1989. At the present time, he heads the Pegasus Toroidal Experiment and directs collaborative experiments on the DIII-D National Fusion Facility. Professor Fonck is a fellow of the American Physical Society and served as president of the University Fusion Association for the 1999-2000 term. He is a member of several program advisory committees for large fusion science experiments, and served on the DOE Fusion Energy Sciences Advisory Committee subpanel for U.S. participation in ITER. He also served as a member on the NRC's Fusion Science Assessment Committee. Currently, he is chair of the Organizing Committee for the American Physical Society's (APS's) Topical Conference on High-Temperature Plasma Diagnostics. His research is in experimental studies of high-beta plasmas in toroidal geometries, plasma turbulence, and high-temperature plasma diagnostic development. He was awarded the 1999 APS Award for Excellence in Plasma Physics Research for his work on measurements of turbulence in high-temperature plasmas. Professor Fonck is a principal investigator on grants from the Office of Fusion Energy Sciences of the Department of Energy.

JOHN N. BAHCALL is a professor at the Institute for Advanced Study in Princeton. He graduated from Harvard University with a Ph.D. in physics in 1961. He then had the following appointments: at Indiana University, he was a research fellow in physics (1960-1962); at the California Institute of Technology, he served as a research fellow, assistant professor, and associate professor of physics (1962-1970); at the Institute for Advanced Study, he has been a member (1968-1969 [term II], 1969-1970), professor of natural sciences (1971-1997), and Richard Black Professor of Natural Sciences (1997 to the present). In addition, Dr. Bahcall has held the following positions: at-large member, interdisciplinary scientist, Hubble Telescope Working Group (1973-1992); councilor, president, American Astronomical Society (1978-1981, 1990-1992, respectively); chair, National Academy of Sciences, Section on Astronomy (1980-1983); chair, NRC, Astronomy and Astrophysics Survey Committee (1989-1991); chair, NRC Panel on Neutrino Astrophysics (1994-1995); chair, U.S. National Committee of the International Astronomical Union (1996-1998); chair, National Underground Science Laboratory Committee (2001). Among the awards and honors that Dr. Bahcall has received are the Warner Prize, American Astronomical Society (1970); Sloan Foundation Fellow (1968-1971); membership in the American Academy of Arts and Sciences; James Arthur Prize Lecturer, Harvard-Smithsonian Center for Astrophysics (May 1988); NASA Distinguished Public Service Medal (1992); National Medal of Science (1998); and in 2003, the Russell Prize of the American Astronomical Society, the Benjamin Franklin Medal in Physics, the Gold Medal of the Royal Astronomical Society, and the Dan David Prize. Dr. Bahcall's research interests include astrophysics, space astronomy, and weak interactions. He is an expert in solar fusion processes. Dr. Bahcall is a member of the National Academy of Sciences.

GORDON A. BAYM has been a faculty member of the University of Illinois at Urbana-Champaign since 1963. He obtained his Ph.D. in 1960 from Harvard University and did postdoctoral work at the Institute for Theoretical Physics (now the Niels Bohr Institute) in Denmark and at the University of California at Berkeley. He has had a long and distinguished research career in the theory of many-body systems, with interests ranging from low-temperature and condensed-matter physics, quantum fluids, and, most recently, Bose-Einstein condensates; to astrophysics and in particular neutron stars; to nuclear physics, including ultra-relativistic heavy ion collisions. His work, multidisciplinary in character, melds basic theoretical physics concepts from condensed matter to nuclear to elementary particle physics. He has served on numerous advisory panels for research agencies and for various international organizations. He received the Alexander von Humboldt Senior Scientist Award in 1983 and the Hans A. Bethe Prize of the American Physical Society in 2002. He is a member of the National Academy of Sciences (former chair of the Physics Section) and the American Philosophical Society and a fellow of the American Academy of Arts and Sciences.

IRA B. BERNSTEIN, a theoretical plasma physicist, is professor emeritus in the Department of Mechanical Engineering and Physics at Yale University. He received his bachelor's degree in chemical engineering from City University of New York and his Ph.D. from New York University. He was a research scientist at the Westinghouse Research Laboratories (1950-1954), a senior research scientist at the Princeton Plasma Physics Laboratory (1954-1964), and has been a professor at Yale since 1964. He has been a consultant to RCA Laboratories, Los Alamos Scientific Laboratory, Lawrence Livermore National Laboratory, the Naval Research Laboratory, and the United Technologies Research Laboratory. He is a recipient of the Maxwell Prize of the American Physical Society and a member of the National Academy of Sciences. He has served on the Fusion Policy Advisory Committee and Fusion Energy Sciences Advisory Committee of the Department of Energy, and on the NRC's Plasma Physics Committee and Board on Physics and Astronomy.

STEPHEN C. COWLEY earned his Ph.D. from the Department of Astrophysical Sciences at Princeton University in 1985. Following his graduation he served as a lecturer at Corpus Christi College at Oxford University and as a senior scientific officer at the U.K. Atomic Energy Authority (Culham Laboratory). He then returned to the United States to work at the Princeton Plasma Physics Laboratory and later accepted a position as professor at the University of California at Los

Angeles (UCLA). Since 2001, Dr. Cowley has been a professor at Imperial College London at the Blackett Laboratory. His research interests at Imperial include fusion theory, plasma and atomic theory associated with x-ray laser development, space and astrophysical plasmas, and multiphoton processes. Dr. Cowley served in 1997 on the FESAC International Thermonuclear Experimental Reactor (ITER) physics review panel. He has served as a member of the organizing committee for the annual Sherwood Fusion Theory meeting and as chair of the NRC's Plasma Science Committee (1999-2001). Dr. Cowley was also a member of the NRC's Physics Survey Overview Committee, which produced the overview volume for the *Physics in a New Era* decadal physics survey. He is currently serving on the review committee for *Physical Review Letters*. Dr. Cowley is a fellow of the APS, the recipient of a number of awards for excellence in teaching at UCLA, and the recipient of a number of fellowships, including the Harkness Fellowship and the Charlotte Elizabeth Proctor Fellowship.

EDWARD A. FRIEMAN is an emeritus member of the board of directors of Science Applications International Corporation (SAIC), research professor at the Institute of Geophysics and Planetary Physics, and director emeritus of the Scripps Institution of Oceanography. He previously served as vice chancellor for marine sciences at the University of California at San Diego. Earlier he was deputy director of the Princeton Plasma Physics Laboratory and director of energy research for the U.S. Department of Energy. His current research interests are science and public policy related to sustainability and fusion development, the global environment, and energy research and development. In the past he has carried out research on theoretical plasma physics, hydromagnetics, hydrodynamic stability, and astrophysics. Dr. Frieman graduated in 1951 with a Ph.D. from the Polytechnic Institute of Brooklyn. He has served as chair of the NRC Board on Sustainable Development and the NRC Board on Global Change. Dr. Frieman is a fellow of the American Physical Society, a member of the National Academy of Sciences, and a member of the American Philosophical Society. He received the Distinguished Service Medal from the Department of Energy, the Department of the Navy Superior Public Service Award, and the James Clerk Maxwell Prize from the Division of Plasma Physics (DPP) of the APS.

WALTER GEKELMAN is a professor of physics at the University of California at Los Angeles. He received his Ph.D. in physics from the Stevens Institute of Technology in 1972. His research interests include exploring under controlled laboratory conditions fundamental plasma processes that play a major role in the behavior of naturally occurring plasmas. These phenomena are manifest in the auroral ionosphere, the magnetosphere, the solar wind, the solar corona, and the interstellar medium. Other topics that Professor Gekelman has studied are magnetic field-line reconnection and linear and nonlinear plasma waves, including recent studies of Alfvén waves caused by rapidly expanding plasma. He was responsible for the construction of and now operates the Large Plasma Device at UCLA, a unique user facility dedicated to the experimental study of a broad range of plasma phenomena. He is a current member of the NRC Plasma Science Committee. Professor Gekelman is an APS-DPP fellow and has been on the DPP executive committee and education outreach and nominating committees. He has won numerous UCLA awards for excellence in teaching and was an APS-DPP distinguished lecturer.

JOSEPH HEZIR is the cofounder and managing partner of the EOP Group, Inc., a consulting company that specializes in regulatory strategy development and problem solving and in identifying newly created government business opportunities formed from mergers, acquisitions, joint ventures, and new markets. Mr. Hezir served for 18 years in the White House Office of Management and Budget (OMB), working as a budget examiner in the Environment Branch and later becoming a senior budget examiner for energy technology programs. In 1982, he joined the Corporate Planning Department of Exxon Research and Engineering Company, specializing in the development of technology forecasts. He returned to OMB in 1983 as chief of the Non-Nuclear Energy Branch. From 1986 to 1992 he served as the OMB deputy associate director for energy and science, with oversight responsibility for the budgetary, regulatory, legislative, and policy development activities of the Department of Energy, National Aeronautics and Space Administration, National Science Foundation, Tennessee Valley Authority, Nuclear Regulatory Commission, and Smithsonian Institution. Currently a member of the Critical Technologies Sub-Council of the Competitiveness Policy Council, Mr. Hezir is also a former member of the NASA Advisory Council and the board of directors of the National Capital Area Chapter of the American Red Cross. He continues to serve as a member of the Red Cross Personnel Advisory Committee. Mr. Hezir completed undergraduate studies in chemical engineering at Carnegie Mellon University. He worked as a research engineer for St. Joe Minerals Corporation and for Carnegie Mellon and as a consultant on environmental and energy issues. He then completed graduate studies at Carnegie Mellon in urban and public affairs, specializing in environmental and energy policy. He also served as an adviser to Allegheny County, Pennsylvania, and as an intern with the New York City Environmental Protection Administration. He has served on a number of NRC panels: the Committee on Cost of and Payment for Animal Research, the Committee on Developing a Federal Materials Facilities Strategy, and the Committee on the Formation of the National Biological Survey.

WILLIAM M. NEVINS received his Ph.D. in physics from the University of California at Berkeley in 1979 and did postdoctoral research at the Princeton Plasma Physics Laboratory before moving to the Lawrence Livermore National Laboratory (LLNL), where he is now a senior scientist in the Fusion Energy Program. His research interests include microturbulence, both kinetic and magnetohydrodynamic (MHD) instabilities in mirror machines (the major experiment at LLNL in the early 1980s), and the absorption of intense microwave pulses by plasmas (a key issue for the Microwave Tokamak Experiment at LLNL in the late 1980s). Dr. Nevins spent most of the 1988-1992 period working on the ITER conceptual design activities (CDA). He is currently principal investigator for the Plasma Microturbulence Project—a collaboration between LLNL, PPPL, the University of Maryland, University of Colorado, UCLA, and General Atomics devoted to the study of plasma microturbulence by direct numerical simulation. Dr. Nevins is a fellow of the APS, an associate editor of *The Physics of Plasmas,* and a member of the editorial board of *Nuclear Fusion*. He has served on several panels of the Fusion Energy Sciences Advisory Committee—including the 1995 FESAC panel, which recommended a science-based fusion energy program, and the 2001 and 2002 FESAC panels, which recommended that the U.S. program proceed with a burning plasma experiment.

RONALD R. PARKER is a professor of nuclear engineering and electrical engineering and computer science at the Massachusetts Institute of Technology (MIT). He obtained his Ph.D. in electrical engineering at MIT in 1967. The honors that Professor Parker has received include the Energy Research and Development Administration Distinguished Associate Award; fellow, American Physical Society; APS Award for Excellence in Plasma Physics; and membership in the National Academy of Engineering. From 1992 to 1998, he was on leave from MIT to serve as ITER deputy director and as head of the ITER Co-Center in Garching, Germany, where he was responsible for the design of the ITER in-vessel systems. After resuming academic duties at MIT in 1998, Professor Parker returned to experimental work on the Alcator C-Mod tokamak, with lead responsibility for a major new initiative aimed at developing steady-state modes of operation based on the combination of radio frequencies and bootstrap current drive. In addition, he has recently initiated a new look at fusion-fission hybrids, including the use of fusion reactors to transmute fission-produced actinides and to burn new fission fuels (thorium) with minimal actinide production.

CLAUDIO PELLEGRINI received the Laurea in Fisica cum laude in 1958 and the Libera Docenza in 1965 from the University of Rome. From 1958 to 1978 he worked at the Frascati National Laboratory of the Italian Nuclear Physics Institute.

In 1965 he was appointed group leader of the Accelerator Physics Theory Group, and in 1976, division head. In 1978 he joined the Brookhaven National Laboratory, where he was head of the Accelerator Physics Section of the National Synchrotron Light Source. At Brookhaven he also served as associate chair of the National Synchrotron Light Source and co-chair of the newly formed Center for Accelerator Physics. In 1989 Professor Pellegrini joined the faculty of the UCLA Department of Physics. He has been a member of the High Energy Physics Advisory Panel of the Department of Energy, the Scientific Policy Committee of the Stanford Linear Accelerator Center, the Cornell University Nuclear Physics Laboratory, and the Free Electron Laser Center at Vanderbilt University. Professor Pellegrini is a fellow of the American Physical Society and in 1996 he was elected chair of the APS Division of Physics of Beams. He has also been the chair of the Panel on Advanced Accelerators of the International Committee for Future Accelerators. He is currently a member of the NRC Plasma Science Committee. Professor Pellegrini was awarded the International Free Electron Laser Prize in 2000, and the Wilson Prize of the American Physical Society in 2001. At the present time, he is chair of the UCLA Department of Physics and Astronomy.

BURTON RICHTER is the Paul Pigott Professor of Physical Sciences at Stanford University and the director emeritus of the Stanford Linear Accelerator Center (SLAC). He received his Ph.D. from MIT in 1956. He has produced more than 300 publications in high-energy physics, accelerators, and colliding beam systems, and won the 1976 Nobel Prize for his pioneering particle physics work at SLAC. Dr. Richter has received many other awards, including Loeb Lecturer, Harvard University (1974); DeShalit Lecturer, Weizmann Institute (1975); and the E.O. Lawrence Medal (DOE) (1976). He is a fellow of the American Academy of Arts and Sciences, APS, and American Association for the Advancement of Science. Dr. Richter was president of the International Union of Pure and Applied Physics (1999-2002) and the American Physical Society (1995). He is a member of the Secretary of Energy Advisory Board, as well as holding a number of other board directorships and advisory committee memberships. He is a member of the National Academy of Sciences.

CLIFFORD M. SURKO is a professor of physics at the University of California at San Diego. He received his Ph.D. from the University of California at Berkeley in 1968. He was a member of the technical staff and a department head at AT&T Bell Laboratories, Murray Hill, New Jersey (1970-1988). His research interests include experimental studies of plasma physics, fluid and nonlinear dynamics, and condensed-matter physics. His current research involves the creation of positron plasmas and beams, studies of plasma physics with positrons, and positron-matter interactions. He is a fellow of the APS and the AAAS and is currently a member of the executive committee of the APS Plasma Physics Division. In 1995 he co-chaired the NRC plasma science study.

TONY S. TAYLOR is the director of the Experimental Science Division and deputy program director for the DIII-D tokamak experiment at General Atomics. His research interests include MHD stability and performance optimization in tokamak plasmas. He received the 1994 APS award for excellence in plasma physics research, and he is an APS fellow. Dr. Taylor has been a member of FESAC and served on the FESAC Burning Plasma Panel.

MICHAEL A. ULRICKSON received his Ph.D. in nuclear physics at Rutgers University in 1975. Dr. Ulrickson began investigating the properties of graphites for use as plasma-facing components (PFCs) at the Princeton Plasma Physics Laboratory (PPPL) in 1975. He was a member of the Deuterium-Tritium Materials Physics Group that successfully predicted the tritium retention during D-T experiments on the Tokamak Fusion Test Reactor (TFTR). In 1988, he received the Fusion Power Associates Excellence in Fusion Engineering Award for "very important contributions to fusion engineering and in recognition of impressive leadership qualities." After 18 years at PPPL, he joined Sandia National Laboratories to manage the Fusion Technology Department. From 1993 to 1998, he coordinated the U.S. PFC research supporting ITER and was the task area coordinator for the international research and development effort on PFCs for ITER. In 1995, he received a certificate of merit from the Office of Fusion Energy at the Department of Energy and the ITER Home Team for his "outstanding performance on behalf of the U.S. ITER Home Team in the field of divertor development and coordination of the four-party R&D effort." Since 1999, he has been project manager for liquid surface PFC research in the United States and directed the design of PFCs for the Fusion Ignition Research Experiment (FIRE) burning plasma device.

MICHAEL C. ZARNSTORFF is the head of the physics team for the National Compact Stellarator Experiment. He received his Ph.D. in physics in 1984 from the University of Wisconsin at Madison with the thesis "Experimental Observation of Neoclassical Currents" on the first experimental observation of the bootstrap current. During his graduate work, he also worked in the Laser Program at the Lawrence Livermore National Laboratory and was co-owner of a small company doing contract computer systems development. After receiving his Ph.D., he joined the Princeton Plasma Physics Laboratory, where he became one of the leaders of the experimental program on TFTR. Dr. Zarnstorff's research included the first observation of the bootstrap current in a tokamak, tests of a number of transport theories, the effect of the current profile on tokamak confinement, fine-scale structure of the temperature profile, and methods to control and suppress anomalous transport. In addition, he clarified the general interpretation of the motional Stark effect and vertical charge-exchange-recombination diagnostics. He has collaborated on other experiments in the United Kingdom, Japan, and Germany, as well as in the United States. Dr. Zarnstorff was a co-discoverer of the Supershot and Enhanced-Reversed-Shear regimes of enhanced confinement in TFTR. In 1995, he was named a distinguished research fellow of PPPL. He teaches in the Astrophysical Sciences Department at Princeton University. He is a fellow of the American Physical Society and served as a DPP/APS distinguished lecturer. He has served on numerous review and advisory committees within the fusion program. His current research focus is on understanding how three-dimensional shaping of magnetic fields and equilibria affects plasma MHD stability and transport.

ELLEN G. ZWEIBEL is professor of astronomy and physics at the University of Wisconsin at Madison, where she moved in January 2003. Previously she was a professor of astrophysics and a fellow of the Joint Institute for Laboratory Astrophysics at the University of Colorado at Boulder. She chaired her department from 1989 to 1992 and chaired JILA from 2000 to 2002. Her research interests are theoretical astrophysics and plasma science. Dr. Zweibel was a member of the NRC's Committee on Astronomy and Astrophysics, the Committee on Strengthening the Linkages Between the Sciences and Mathematics, the Plasma Science Committee, the Panel on Opportunities in Plasma Science and Technology, and the Theoretical Astrophysics and Solar Astrophysics panels of the Astronomy and Astrophysics Survey Committee in 1991 and 2001. She is a fellow of the American Physical Society. She received a Ph.D. in astrophysical sciences from Princeton University in 1977.

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Glossary

Advanced Reactor Innovation Evaluation Study (ARIES): A comprehensive study of tokamak fusion power plants undertaken by a collaboration of U.S. fusion laboratories in the early 1990s. Four designs were studied: ARIES-I, a device based on modest extrapolations from the tokamak physics database; ARIES-II and ARIES-IV, two second stability devices, which differed in their fusion power core composition; and ARIES-III, which, unlike the others, utilized the deuterium-helium-3 fusion reaction instead of the deuterium-tritium reaction. Other more advanced configurations have been studied as well; ARIES-RS used a reversed-shear (RS) tokamak while ARIES-AT studied an advanced tokamak (AT).

Advanced tokamak (AT): A tokamak that would operate continuously, with the current driven by a combination of noninductive external drive and the natural pressure-driven currents that occur in plasmas. ATs require careful optimization of pressure and confinement. The continuous operation is highly desirable for fusion power production.

Alfvén wave: A fundamental plasma phenomenon that is primarily magnetohydrodynamic in character, involving oscillation of the magnetic field and, in some cases, plasma pressure. In tokamaks, these waves are typically strongly damped (they would spontaneously decay if externally excited).

Alpha particles: He^{2+}, a positively charged particle consisting of two protons and two neutrons; denoted by the Greek letter alpha (α); a helium-4 nucleus. An alpha particle is a typical product of fusion reactions.

Auxiliary heating: Power applied to tokamaks to raise the internal temperature when the contribution from ohmic heating is relatively small. Auxiliary heating usually uses neutral beams or radio-frequency waves.

Beta: $\beta = p/(B^2/2\mu_o)$. The ratio of plasma gas pressure (p) to magnetic field pressure ($B^2/2\mu_o$) in a tokamak; p is the gas pressure in pascals (newtons per square meter), B is the magnetic field strength in teslas, and $\mu_o = 4\pi \times 10^{-7}$ henrys per meter.

Beta limit: Maximum beta attainable, usually resulting from a deterioration in the confinement.

Blanket: The physical system surrounding the hot plasma. It provides shielding and absorbs fast neutrons, converts the energy into heat, and produces tritium. Blanket technology for the practical application of harnessing fusion energy is still under development. The ultimate design may include a liquid metal such as molten lithium, which produces tritium when it captures neutrons.

Bootstrap current: In 1970, theorists predicted that a toroidal electric current will flow in a tokamak that is fueled by energy and particle sources that replace diffusive losses. This diffusion-driven bootstrap current, which is proportional to beta and flows even in the absence of an applied voltage, could be used to provide the confining magnetic field: hence the concept of a bootstrap tokamak, which has no toroidal voltage. A bootstrap current consistent with theory was observed many years later on the Joint European Torus and the Tokamak Fusion Test Reactor; it now plays a role in the design of experiments and power plants (especially advanced tokamaks).

Burning plasma: A fusion plasma in which alpha particles from the fusion reactions provide the dominant heating of the plasma.

Confinement: The containment of plasma particles and energy within a container for some extended period of time. A fusion reactor must confine the fuel plasma long enough at high enough density and temperature in order to be economically feasible.

Confinement, magnetic: A method of containing a plasma or charged particles in a finite region using magnetic fields. Charged particles travel in helical paths around the magnetic field lines, which confine their motion to the local vicinity of the magnetic field. A properly shaped magnetic field prevents particles from escaping the confining field. A tokamak is one example of a magnetic-confinement device.

Confinement time: The amount of time it takes for energy or particles to leave the plasma.

Current distribution: The variation of plasma current density within the plasma, usually expressed as a function of the distance from the magnetic axis.

Current drive: Any of a number of means to maintain or increase electrical current in a plasma by using external devices such as neutral-beam or radio-frequency power generators.

Deuterium: Isotope of hydrogen having one proton and one neutron in its nucleus and an atomic mass of 2. Deuterium behaves like hydrogen in chemical reactions, but behaves much differently in nuclear reactions.

Deuterium-tritium (D-T) reaction: The fusion of a deuteron and a triton, leading to the release of energy and the production of a helium-4 nucleus (alpha particle) and a neutron. The reaction reaches its maximum cross section at fairly low energy (≈40 to 50 keV). Accordingly, it will be the preferred fuel in fusion power plants. The reaction is $D + T \rightarrow {}^4He + n + \text{energy}$.

Deuteron: Nucleus of a deuterium atom.

DIII-D: The third-generation tokamak developed by General Atomics in San Diego, California, the largest operational tokamak in the United States. Its principal parameters are these: major radius, 1.7 m; minor radius, 0.7 m; toroidal field, 2.1 T; plasma current, 2 MA.

Disruption, disruptive instability: A complex phenomenon involving magnetohydrodynamic instability, which results in rapid heat loss and termination of a discharge. Plasma control may be lost, triggering a vertical displacement event whereby the whole plasma moves up (or down) away from its equilibrium position. This phenomenon places a limit on the maximum density, pressure, and current in a tokamak.

Divertor: A magnetic field configuration affecting the edge of the confinement region, designed to divert impurities and helium ash to a target chamber.

Edge-localized mode (ELM): An instability that occurs in short, periodic bursts during the high-confinement regime in divertor tokamaks. It causes transient heat and particle loss into the divertor, which can be damaging.

FESAC: Fusion Energy Sciences Advisory Committee of the U.S. Department of Energy.

Fusion: A nuclear reaction in which two light atomic nuclei combine to form another element with the release of energy. The production of all elements up to nickel (Ni) happens via the fusion process (nucleosynthesis). Neutron bombardment of medium-sized nuclei heavier than nickel produces heavier nuclei. These processes occur in stars and are responsible for the presence of essentially all of the elements heavier than helium in the universe.

Greenwald limit: The Greenwald normalized density is given by $n_{20}\pi a^2/I_p$, where n_{20} is the electron density expressed in units of 10^{20} m^{-3}, a is the plasma minor radius in meters, and I_p is the plasma current in megamperes. In many tokamaks this value does not exceed 1, so the Greenwald density is a measure of the density limit for a tokamak.

Helium ash: Fusion reactions in a deuterium-tritium plasma produce energetic alpha particles (helium nuclei), which heat the plasma as they slow down. Once this heating has happened, the alpha particles have no further use: They constitute helium ash, whose removal and replacement by deuterium-tritium fuel are required to prevent dilution of the plasma.

H-mode: A high-confinement regime that has been observed in tokamak plasmas. It develops when a tokamak plasma is heated above a characteristic power threshold, which increases with density, magnetic field, and machine size. It is characterized by a sharp temperature gradient near the edge (resulting in an edge "temperature pedestal"), edge-localized modes, and about a 100 percent increase in energy confinement time compared with that of the normal low-confinement regime, or L-mode.

Ion cyclotron heating: Auxiliary heating method using radio-frequency waves at frequencies (about 20 to 50 MHz) matching the frequency at which ions gyrate around the magnetic field lines.

ITER: International Thermonuclear Experimental Reactor. The ITER experiment will be a burning plasma experiment based on the tokamak concept—the leading magnetic-confinement fusion concept, named after the Russian word for a toroidally (or doughnut) shaped magnetic field. ITER is expected to be larger than existing tokamaks, with a major radius of 5 to 8 m, and is expected to use superconducting magnets to confine the hot plasma. The negotiations to start the ITER project are being attended by the European Union, Russia, Japan, China, South Korea, Canada, and the United States (which rejoined the negotiations in January 2003).

Joint European Torus (JET): The largest tokamak in the world with a major radius of 2.96 m. It is sited at Culham in the United Kingdom.

JT-60U: The flagship tokamak of the Japanese magnetic-confinement fusion program, similar in size to JET.

L-mode: The "normal" low-confinement regime, opposite to the high-confinement regime, or H-mode, of additionally heated tokamak operation.

Magnetohydrodynamics (MHD): A mathematical description of the plasma and magnetic field, which treats the plasma as an electrically conducting fluid. Often used to describe the bulk, relatively large-scale properties of a plasma.

Major radius: The radius from the center line of the torus to the axis that is the center of the small cross section.

MFE: Magnetic fusion energy; the use of magnetic-confinement configurations for fusion plasmas to generate electrical energy.

Minor radius: The radius of the small cross section of a torus.

Mode: Wave or oscillation in a plasma.

Neoclassical tearing mode: The plasma state that occurs when the magnetic island produced by a tearing mode perturbs the bootstrap current, which further amplifies the island and degrades confinement or leads to a disruption.

Neoclassical theory: Classical collisional plasma transport theory, corrected for toroidal effects. The neoclassical theory predicts the existence of the bootstrap current.

Neutral beam: An energetic beam of neutral particles. It is typically produced by accelerating charged particles, or ions, which are subsequently neutralized in an electron exchange process.

Neutral-beam heating: In magnetic fusion, neutral beams use isotopes of hydrogen and are primarily used to heat the plasma.

Ohmic heating: Inductive heating created by using a transformer to drive a current in the plasma. This heating is necessarily pulsed.

Pedestal, temperature: In the high-confinement regime, the temperature at the top of the steep temperature gradient region at the plasma edge.

Plasma: A state of matter characterized by unbound negative electrons and positive ions that may conduct electrical current. Plasma is often called the fourth state of matter, along with the other three: solids, liquids, and gases. It is estimated that more than 99 percent of matter in the universe exists as plasma; examples include stars, nebulae, and interstellar particles. The temperature of a typical plasma may be 100,000 K or more, and plasmas vary in particle density from about 10^6 per cubic meter (solar wind) to 10^{30} per cubic meter (the core of a star). Plasmas are relatively rare natural occurrences on Earth, but many applications of plasma discharges have been found. Examples of plasma can be found in lightning, the aurora borealis, fluorescent and neon-type lights, arc welding, and machines built to study nuclear fusion.

Plasma pressure: Proportional to the product of plasma density and temperature. In magnetic-confinement devices, this outward pressure is counterbalanced by magnetic forces.

Plasma rotation: Bulk rotation of the plasma in the toroidal or poloidal direction. Neutral-beam injection can cause plasma rotation in the toroidal direction at velocities of typically 100 km/s.

Poloidal field: The component of the magnetic field parallel to the minor circumference. The poloidal field is essential for confinement and, in a tokamak, is generated by the plasma current (cf. **Stellarator**); this is in contrast to the larger toroidal field, which is generated externally.

Reconnection, magnetic: Involves the breaking and reconnecting of oppositely directed magnetic field lines in a plasma. In the process, magnetic field energy is converted to plasma kinetic and thermal energy.

Reversed-field pinch: A toroidal magnetic-confinement device in which the poloidal and toroidal fields are of comparable magnitude. To maintain stability, the toroidal field reverses close to the edge of the plasma when a critical plasma current is exceeded.

RF: Radio frequency—electromagnetic energy having a frequency from 10^4 to 10^{12} Hz.

Scaling laws: Empirical or theoretical expressions for how various plasma phenomena (e.g., confinement, power threshold, and so on) vary with the tokamak conditions using a range of free parameters to be fixed by "best fits" of the scaling law to tokamak data. They are particularly useful for predicting the performance of future tokamaks.

Solar corona: The Sun's outer atmosphere, which displays a variety of features including streamers, plumes, and loops.

Spherical torus, spherical tokamak: A very low aspect ratio torus approximating to a sphere (although topologically remaining a torus). Very low aspect ratio tokamaks are often called spherical tokamaks.

Stellarator: A toroidal magnetic-confinement device whose poloidal field is generated by external helical coils (unlike the tokamak, in which it is generated by an internal current induced by transformer action). The absence of a plasma current gives stellarators significant potential advantages over tokamaks as fusion power plants (no disruptions, no current drive, and no stability control system). There are a number of different stellarator configurations: for example, the torsatron, heliotron, and helias. In general, stellarators have not been as successful as tokamaks, though a considerable level of research continues—notably in Germany, Spain, the United States, Russia, and Japan.

Tearing mode: A class of resistive magnetohydrodynamic instability that has been predicted theoretically in tokamaks.

Tokamak: The leading magnetic-confinement fusion concept, named after the Russian word for a toroidally (or doughnut) shaped magnetic field. The field the long way around the torus is the toroidal field; it is the main confining field for the particles. The toroidal field is produced from a set of poloidally constructed electromagnets.

Tokamak Fusion Test Reactor (TFTR): Was the largest U.S. device, located at the Princeton Plasma Physics Laboratory, operating from 1982 to 1997. TFTR performed a major campaign using deuterium and tritium fuel between 1993 and 1997. It had a relatively high magnetic field of 5 T and a circular cross section.

Tore Supra: A large tokamak with superconducting toroidal magnets and an actively cooled first wall. It is located in Cadarache, France.

Toroidal: Having the specific geometrical shape of a torus. The toroidal direction is along the large circular axis of the torus.

Torus: The shape of a simple doughnut. It is also the term used to describe the vacuum vessel used in tokamak fusion research.

Transport: The processes by which particles and energy in the center of the plasma are lost to the edge of the plasma.

Transport barrier: In certain operational scenarios (e.g., the high-confinement mode, or H-mode) a region of low transport exists, giving rise to a steep pressure gradient. Such a region is referred to as a transport barrier.

Tritium: Isotope of hydrogen having one proton and two neutrons in its nucleus. Tritium is radioactive, with a half-life of 12.3 years, and is essentially nonexistent in nature. Tritium can be produced by bombarding lithium with a neutron and inducing a fission reaction. $^6\text{Li} + n \rightarrow \text{T} + {}^4\text{He} + 4.8\ \text{MeV}$ or $^7\text{Li} + n \rightarrow \text{T} + {}^4\text{He} + n - 2.5\ \text{MeV}$.

Triton: Nucleus of a tritium atom.

Turbulence: Randomly fluctuating, as opposed to coherent, wave action. For example, the turbulent surface of water beneath a waterfall can only be described in terms of its averaged properties, such as the scale and duration of fluctuations, whereas a more systematic description can be given to waves on the surface of a still pond.