

BURNING PLASMA
Bringing a Star to Earth

**UNEDITED PREPUBLICATION COPY
FINAL WORDING SUBJECT TO CHANGE**

***For Public Release on
Friday, September 26, 2003, 4:00pm***

Burning Plasma Assessment Committee
Plasma Science Committee
Board on Physics and Astronomy
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Grant No. DE-AT01-02ER54676 between the National Academy of Sciences and the Department of Energy. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-0XXXX-X
Library of Congress Catalog Card Number 97-XXXXX

Copyright 2003 by the National Academy of Sciences. All rights reserved.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

BURNING PLASMA ASSESSMENT COMMITTEE

JOHN F. AHEARNE, Sigma Xi Duke University, *Co-chair*
RAYMOND FONCK, University of Wisconsin at Madison, *Co-chair*
JOHN N. BAHCALL, Princeton University
GORDON A. BAYM, University of Illinois at Urbana-Champaign
IRA B. BERNSTEIN, Yale University
STEPHEN C. COWLEY, Imperial College London
EDWARD A. FRIEMAN, SAIC
WALTER GEKELMAN, University of California at Los Angeles
JOSEPH HEZIR, EOP Group, Inc.
WILLIAM M. NEVINS, Lawrence Livermore National Laboratory
RONALD R. PARKER, Massachusetts Institute of Technology
CLAUDIO PELLEGRINI, University of California at Los Angeles
BURTON RICHTER, Stanford Linear Accelerator Center
CLIFFORD M. SURKO, University of California at San Diego
TONY S. TAYLOR, General Atomics
MICHAEL A. ULRICKSON, Sandia National Laboratories
MICHAEL C. ZARNSTORFF, Princeton Plasma Physics Laboratory
ELLEN G. ZWEIBEL, University of Wisconsin at Madison

Staff

DONALD C. SHAPERO, Director, Board on Physics and Astronomy
TIMOTHY I. MEYER, Study Director (from August 2003)
MICHAEL H. MOLONEY, Study Director (May 2002–July 2003)

PLASMA SCIENCE COMMITTEE

THOMAS M. O'NEIL, University of California at San Diego, *Chair*
MICHAEL S. BARNES, Applied Materials
ALLEN BOOZER, Columbia University
JOHN CARY, University of Colorado at Boulder
CYNTHIA A. CATTELL, University of Minnesota
CARY FOREST, University of Wisconsin, Madison
WALTER GEKELMAN, University of California at Los Angeles
MARK J. KUSHNER, University of Illinois at Urbana-Champaign
DAVID MEYERHOFER, University of Rochester
CLAUDIO PELLEGRINI, University of California at Los Angeles
DMITRI RYUTOV, Lawrence Livermore National Laboratory
STEWART J. ZWEBEN, Princeton University

Staff

DONALD C. SHAPERO, Director, Board on Physics and Astronomy
TIMOTHY I. MEYER, Program Officer
PAMELA A. LEWIS, Project Associate
NELSON QUIÑONES, Project Assistant

BOARD ON PHYSICS AND ASTRONOMY

BURTON RICHTER, Stanford University, *Chair*
ANNEILA I. SARGENT, California Institute of Technology, *Vice chair*
ELIHU ABRAHAMS, Rutgers State University
JONATHAN BAGGER, Johns Hopkins University
GORDON A. BAYM, University of Illinois at Urbana-Champaign
CLAUDE R. CANIZARES, Massachusetts Institute of Technology
WILLIAM EATON, National Institutes of Health
RAYMOND FONCK, University of Wisconsin at Madison
WENDY L. FREEDMAN, Carnegie Observatories
LAURA H. GREEN, University of Illinois at Urbana-Champaign
FRANCES HELLMAN, University of California at San Diego
ERIC P. IPPEN, Massachusetts Institute of Technology
LINDA J. (LEE) MAGID, University of Tennessee at Knoxville
THOMAS M. O'NEIL, University of California at San Diego
JULIA M. PHILLIPS, Sandia National Laboratories
JOSEPH H. TAYLOR, JR., Princeton University
THOMAS N. THEIS, IBM Thomas J. Watson Research Center
CARL E. WIEMAN, University of Colorado/JILA

Staff

DONALD C. SHAPERO, Director
ROBERT L. RIEMER, Senior Program Officer
BRIAN D. DEWHURST, Research Associate
TIMOTHY I. MEYER, Program Officer
PAMELA A. LEWIS, Project Associate
NELSON QUIÑONES, Project Assistant
VAN AN, Financial Associate

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 last decade great strides have been made toward that goal leading the fusion research program to a decision point—are we 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 fifty 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 in July 2002 at the request of the DOE’s Office of Science.¹ The committee was charged with assessing the importance of a burning plasma experimental program, the scientific and technical readiness to undertake a burning plasma experimental program, and 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 in a series of NRC studies that have considered the direction of the U.S. fusion program over the last decade—the 1995 report *Plasma Science: From Fundamental Research to Technological Applications*² and the 2001 report of the Fusion Science Assessment Committee (FUSAC),³ both of which 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” (p. 2).

¹ The establishment of an NRC committee on a burning plasma experiment was also mentioned in legislation under consideration by Congress at the time of the committee’s establishment.

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.

The third item of the committee’s task was to provide “[a]n 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 use of fusion for commercial energy purposes. The major work of the 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.

The committee’s membership 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 aspect 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 United States entering ITER negotiations.⁴ Issued on December 20, 2002, the interim report⁵ recommended that the United States re-enter the ITER negotiations with a view to full participation in the experiment. Subsequent to the report’s publication, President Bush announced that the government would join the negotiations, and a U.S. team has since been active.

In the context of rejoining the ITER negotiations, the interim report offered some preliminary findings and conclusions on the importance and readiness issues, but left much of the charge untouched. Since completing its interim report, the committee focused on the remainder of its charge and, most importantly, 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?

⁴ ITER, the International Thermonuclear Experimental Reactor, will be a burning plasma experiment based on the tokamak concept—the leading magnetic confinement fusion whose name comes from the Russian word for a toroidally (or donut) shaped magnetic field. ITER is expected to be larger than existing tokamaks, with a major radius of 5 to 8 meters, 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, and the United States.

⁵ The text of the Burning Plasma Assessment Committee’s letter report has been reproduced in Appendix E and is available online at <http://books.nap.edu/openbook/N1000487/html/index.html>.

- 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 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 question (1)?
- 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 these questions and in approaching the execution of its charge the committee received important inputs from the fusion community and others, at its formal meetings⁶ 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 thanks the community for this input and in particular the organizers and participants in the Fusion Workshop held in Snowmass, Colorado, in July 2002. The committee commends all 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 contribution to our work and the completion of this report: Karl Lackner, Dale Meade, Jerry Navratil, Stewart Prager, Bruno Coppi, Robert Hirsch, Ned Sautoff, Marshall Rosenbluth, Stephen Dean, Robert Goldtson, Michael Mauel, Ron Stambaugh, and others. The committee also expresses its deepest gratitude to Michael Moloney, the NRC study director for this committee, and to Don Shapero and Tom O'Neil, 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 difficult task of the final steps in the Academies' review process.

Finally, in presenting our report we would like to thank our colleagues on the committee. The diversity of our 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, our 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 that support its work to develop a prioritized strategy to

⁶ Agendas for the committee's four meetings are provided in Appendix B.

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

Raymond Fonck, co-chair

Burning Plasma Assessment Committee

Acknowledgement 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,
T. Kenneth Fowler, University of California at Berkeley,
Harold K. Forsen, National Academy of Engineering,
Cary B. Forest, University of Wisconsin at Madison,
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

SUMMARY	1
1. NEXT STEPS FOR THE FUSION SCIENCE PROGRAM	10
1.1 Introduction.....	10
1.2 Preparing for a Burning Plasma Experiment	13
1.2.A Scientific Value and Interest.....	14
1.2.B Technological Value and Interest.....	15
1.2.C Readiness to Pursue a Burning Plasma Experiment.....	16
1.2.D The Next Step?.....	18
1.3 Program Structure	19
1.3.A Today’s Balance.....	20
1.3.B Primary Issues of Fusion Science Research.....	22
1.3.C Research Opportunities and Science and Technology Goals for the Next Decade: Direct Support of the Burning Plasma Program on ITER	24
1.3.D Research Opportunities and Science and Technology Goals for the Next Decade: Concept-Optimization Research.....	26
1.3.E Theory, Simulation, and Computation	27
1.3.F The Role of the Universities: Research, Education, and the Fusion Workforce	28
1.3.G The ITER Negotiations and Program Contingency	30
1.4 Striking the Balance.....	32
1.4.A Summary of Findings and Discussion	32
1.4.B Implications for the Fusion Community	34
1.4.C Budget Implications	35
1.4.D Setting Priorities to Strike the Balance	36
1.5 Conclusions and Recommendations—Elements of a Strategically Balanced Fusion Program.....	38
1.5.A Conclusions.....	38
1.5.B Recommendations for a Program Strategy.....	41
1.6 Final Comment.....	43
2. SCIENTIFIC AND TECHNOLOGICAL VALUE AND INTEREST OF A BURNING PLASMA.....	45
2.1 Introduction.....	45
2.2 Scientific Importance of a Burning Plasma for Fusion Energy Science and the Development of Fusion Energy	47
2.2.A Behavior of Self-Sustaining Burning Plasmas.....	47
2.2.B Plasma Turbulence and Turbulent Transport.....	48
2.2.C Stability Limits to Plasma Pressure.....	49
2.2.D Controlling Sustained Burning Plasmas	49
2.2.E Power and Particle Exhaust.....	49
2.2.F Conclusion	50

2.3 Scientific Importance of a Burning Plasma for Basic Plasma Physics	50
2.3.A Magnetic Field Line Reconnection	51
2.3.B Plasma Turbulence	51
2.3.C Abrupt Plasma Behavior	51
2.3.D Energetic Particles in Plasmas	52
2.3.F Conclusion	52
2.4 General Scientific Importance of a Burning Plasma.....	52
2.5 Technological Importance for Fusion Energy Science and the Development of Fusion Energy	53
2.5.A Breeding Blanket Development.....	54
2.5.B Tritium Processing	55
2.5.C Magnet Technology.....	55
2.5.D High-Heat-Flux Component Development.....	56
2.5.E Remote Handling Technology.....	56
2.5.F Conclusion	57
3. READINESS FOR UNDERTAKING A BURNING PLASMA EXPERIMENT	63
3.1. Scientific Readiness.....	63
3.1.A Confinement Projections.....	64
3.1.B Operational Boundaries—Plasma Pressure and Current.....	65
3.1.C Mitigation of Abnormal Events.....	66
3.1.D Maintenance of Plasma Purity	67
3.1.E Characterization Techniques	67
3.1.F Plasma Control Techniques	67
3.1.G Conclusion	68
3.2 Technical Readiness.....	68
3.2.A Fabrication of Necessary Components	69
3.2.B Component Lifetime in a Nuclear Environment.....	69
3.2.C Lifetime of Plasma-Facing Components.....	70
3.2.D Tritium Inventory Control.....	70
3.2.E Remote Maintenance	70
3.2.F Fueling, Heating, and Current-Drive Control.....	71
3.2.G Conclusion	71
4. PROGRAM STRUCTURE AND BALANCE	81
4.1 Introduction.....	81
4.2 Fusion Science Issues and Research Portfolio.....	83
4.2.A Plasma Turbulence and Turbulent Transport.....	85
4.2.B Stability Limits to Plasma Pressure.....	85
4.2.C Stochastic Magnetic fields and Self-Organized Systems.....	86
4.2.D Plasma Confinement with Different Types of Magnetic-Field Symmetry	87
4.2.E Control of Sustained High-Pressure Plasmas	87
4.2.F Energetic Particles in Plasmas	88

4.3 Research Opportunities and Science and Technology Goals for the Domestic Fusion Program.....	88
4.3.A Directly Support the Burning Plasma Program on ITER.....	89
4.3.B Develop an Understanding of Paths to Advanced Tokamak Regimes.....	92
4.3.C Test the Effects of Extreme Toroidicity in the Spherical Torus	93
4.3.D Demonstrate Sustainment and Enhanced Confinement in the Reversed Field Pinch	94
4.3.E Explore the Potential for Passive Stability and Steady-State Operation in Three-Dimensional Stellarators with Underlying Magnetic Symmetry	95
4.3.F Explore Novel and Emerging Fusion Science and Technology Concepts ..	95
4.3.G Develop Fusion Technologies to Enable Innovative Fusion Science Experiments and Provide Attractive Long-Term Reactor Concepts	96
4.3.H Partner with International Collaborators.....	97
4.4 Theory and Computation	97
4.5 Workforce Readiness.....	99
4.5.A Aging Workforce and Dwindling Supply	99
4.5.B Recruitment and Basic Scientific and Technical Education	101
4.5.C Specialized training in fusion technology	102
4.6 Program Structure and Its Evolution.....	104
4.6.A Present Structure	105
4.6.B Required Elements of a Balanced Program.....	106
4.6.C Integration of Program Activities.....	108
4.7 Setting Priorities to Strike the Balance	110
APPENDICES	121
A. Charge to the Committee	123
B. Committee Meeting Agendas.....	125
C. Proposed Burning Plasma Experiments	129
D. Community Recommendations.....	133
E. Committee’s Interim Report.....	141
F. Fusion Reactor Concepts.....	153
G. Committee Member Biographies.....	157
GLOSSARY.....	165

Summary

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 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 and has led to the development of magnetic and inertial plasma confinement systems. Carried out in the United States under the sponsorship of the Department of Energy's Office of Fusion Energy Sciences, fusion research 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 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,¹ paraphrased below:

- 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.

Experiments 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 doing so is to understand the physics of the confinement, heating, and stability of burning plasmas as well as to explore the

¹ *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, U.S. Department of Energy, DOE/ER-0684, August 1996.

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 importance of a burning plasma experiment, the readiness 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 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 multi-decade enterprise. It is subject to many unknowns—both technical and societal—that are beyond the scope of this committee's charge. Indeed, 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 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 element 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 requires 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 ITER, 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 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 making this move the fusion community

² ITER, the International Thermonuclear Experimental Reactor, will be a burning plasma experiment based on the tokamak concept—the leading magnetic confinement fusion whose name comes from the Russian word for a toroidally (or donut) shaped magnetic field. ITER is expected to be larger than existing tokamaks, with a major radius of 5 to 8 meters, 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, and the United States.

should focus on the opportunities 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 has not been tasked to set them, it does recommend that the community take part in a real prioritization process for the fusion program. The OFES must take the lead and bring the community to this consensus.

Based on its own assessments and deliberations, the committee concluded 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 understanding 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 tokamak is the only fusion configuration ready for implementing such an experiment.

- **The United States should participate in ITER. If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced fusion science program.**
- **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.**
- **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. Its 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 in ITER also very effectively leverages the U.S. investment in its fusion 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. Those 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 ITER participation will be able to meet the U.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. This, too, is a welcome development.

Notwithstanding the goodwill of all the negotiating parties and the significant progress made to date, there is a possibility that the ITER negotiations could fail. In that case, in order to progress with the development of fusion energy, it will be necessary to look for an alternative approach to a burning plasma experiment 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 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.

- **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 ITER is as yet undetermined, it is clear that the fusion effort requires a strategically balanced program in the context of ITER

³ Department of Energy Assessment of the ITER Project Cost Estimate, November 2002. Available online at http://fire.pppl.gov/doe_iter_lehman.pdf.

participation. In structuring the U.S. fusion program with participation in ITER, it will be important to maintain it as a diversified program 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 ITER. In addition, the pursuit of fusion as an attractive energy source requires the investigation of critical plasma physics and stability issues that are discussed in more detail later in this report (see Section 2.2, “Scientific Importance of a Burning Plasma for Fusion Energy Science and the Development of Fusion Energy”). 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 of understanding 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 Integrated Tokamak Program Activity, which identifies and promotes areas of cross-fertilization and comparative experiments. The international effort should not be limited only to ITER, 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 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 providing new ideas and training opportunities can be expected to continue, throughout the era of the burning plasma experiment and further 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 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 OFES will inevitably lead to decay in facilities and research opportunities and virtually guarantee that the United States will not gain the desired benefits from its investment. Such a reduced effort in the critical activities the U.S. fusion community needs to pursue will increase the risk of the U.S. following rather than leading 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 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 increase its connections 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:⁴

- **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.**

The merit of any of the U.S. fusion science program activities under way now, or envisioned, does not mean that every activity can, or even should, be supported unconditionally. Under any funding scenario that can reasonably be expected, there will be the need to decide the relative priority of activities to pursue at any given time. The choice of what opportunities to pursue—including what 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 should result in a clear ordered list of activities to be pursued. Such a list would identify those areas of science and technology that (1) have the greatest uncertainty or (2) promise the greatest impact for the future of the fusion program.

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 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 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.

⁴These program elements are indeed the three goals of the U.S. fusion program as outlined by DOE/OFES in 1996. The committee affirms these elements as substantive and appropriate for a strategically balanced program.

Having concluded that the United States is ready to take the next critical step in fusion research, the committee recommends implementation of a burning plasma experiment through participation in the ITER project 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

1.1 INTRODUCTION

The search for a means to control thermonuclear fusion has led to the development of magnetic and inertial plasma confinement systems, and 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 Office of Fusion Energy Sciences (OFES) and referred to herein as "the U.S. fusion program"⁵, 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, i.e. where hot fusion plasmas are confined by large magnetic fields.

There has been significant progress in understanding and controlling turbulence and instabilities in high-temperature plasmas, which in turn has led to improved plasma confinement. Theory and modeling are now able to provide useful insights into turbulence and 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 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 1990's at the Tokamak Fusion Test Reactor (TFTR) in the U.S. and the Joint European Torus (JET) in Europe. These plasmas generated up to 16 MW of fusion power for about 1 second, of which 80 percent was in the form of 14 MeV neutrons, which escaped from the plasma, and 20 percent 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 it—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 INTOR (the International Toroidal Reactor), the U.S. Compact Ignition Tokamak (CIT), the U.S.

⁵ 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 implication should be drawn from the omission of this part of the OFES program from our discussion.

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. 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.⁶ 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)² 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. 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 recommended in its interim report that the U.S. fusion program participate in a burning plasma experiment.

During the last 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. 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.

Incorporation of advanced design elements from the fusion science and technology community have resulted in more attractive proposals for the burning plasma experiment. These changes have reduced the estimated cost of such an experiment and allowed the

⁶ 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.

investigation of advanced tokamak features in the burning plasma regime. The designs require 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 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 has led to detailed consideration of such a strategy through the Snowmass process⁷ and the advice of the DOE’s Fusion Energy Sciences Advisory Committee (FESAC). In addition, DOE charged this committee with 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 the 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. (Please see Appendix A for the complete charge to the committee.)

This report answers this charge. The following two chapters describe the compelling scientific importance of and the readiness for a burning plasma experiment, respectively. Chapter 4 discusses the overall structure of the nation’s fusion program.

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

This report focuses on the charge by assessing the scientific readiness for and benefits from participation in a burning plasma experiment. It is important to note that there are many additional issues and activities which are critical to achieving practical fusion energy through magnetic confinement, but which are outside the purview of this committee. These include issues such as the qualification of nuclear materials for long-life operation under high neutron fluences, development of low-activation materials, 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 is 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 more complete development for practical fusion energy will require consideration of 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.

⁷ The Snowmass process engaged the U.S. fusion community in a technical assessment of the options for U.S. participation on a burning plasma experiment. The process culminated in a two-week community conference in July 2002. The outcomes of this assessment were provided to the DOE’s Fusion Energy Sciences Advisory Committee for their consideration of the direction of the U.S. Fusion Program.

1.2 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 is to build a facility capable of achieving a burning plasma.⁸ Demonstrating a burning plasma is the necessary experiment to continue to develop the scientific and technological understanding to proceed towards the development of controlled fusion energy.

A number of experiments ranging from a reactor-scale device using superconducting magnets, to a compact, high-field copper-magnet device, have been considered for implementing a burning plasma experiment (see Appendix C for a discussion of the three current proposed burning plasma projects). On the global scale the greatest effort has been put into realizing the International Thermonuclear Experimental Reactor (ITER), an international facility⁹ that is designed to demonstrate the scientific feasibility of fusion as an energy source, and develop and test key features of the technology that will be required for a fusion power plant. A cut-away figure of the device is shown in figure 1.1.

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 two 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 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 to investigate burning plasma behavior (see Appendix D *Past Community Recommendations*). 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,

⁸ Several reports have considered this issue (see Appendix D for some community efforts in this regard). The National Research Council has also opined on 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." - National Research Council, Fusion Science Assessment Committee (FUSAC) *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, National Academy Press, Washington, D.C., 2001.

⁹ 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.

and on the development of technologies that made advanced facilities and diagnostics available.

With this assertion in mind the U.S. program was considering re-entering the negotiations on ITER when this committee was established. At its first meeting on September 17th, 2002, Dr. Raymond Orbach, Director of the DOE Office of Science, asked this committee to report in 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 *BPAC Interim Report*) was issued on December 20th 2002 in response to that urgent request.

The interim report, and as expanded upon in the later sections 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.

1.2.A 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 which, 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 a full 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-scale¹⁰ fusion experiments that are available to the scientific community today.

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

- Plasma behavior when self-sustained by fusion (burning);

¹⁰ Note “smaller scale” in the context of this report should be interpreted as smaller than the ITER scale.

- 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 the 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. While a burning plasma experiment is designed specifically to investigate the burning plasma state and it cannot replace experiments that are purpose-built to directly address the broader set of basic plasma issues, a burning plasma experiment, and the scientific program leading to and in support of it 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.

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, and only a few examples of these connections are mentioned here. For 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.

1.2.B Technological Value and Interest

Depending on its scale, a burning plasma experiment could offer an 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 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 is the physical system surrounding the hot plasma that 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 a testbed 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 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, 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

1.2.C 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 twelve specific scientific and technical criteria—six 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 as follows.

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, and the present level of uncertainty in these projections is acceptable.

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.

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.

Maintenance of plasma purity Impurities in the plasma, either as 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 inhibiting impurity influx from the first wall and divertor.

Characterization techniques Techniques are available to adequately characterize and evaluate most of the important parameters in a burning plasma.

Plasma control techniques 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.

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.

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.

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.

Tritium inventory control Safety analyses have found that the proposed burning plasma devices meet fusion safety standards, and none require 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

Remote maintenance The required remote maintenance has been demonstrated in operational fusion experiments.

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.

1.2.D The Next Step?

Based on 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 project.¹¹

Notwithstanding 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 timeframe and beyond. This effort will be a challenge, as was recognized in the committee's interim report where it was recommended that:

“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.

¹¹ The committee notes that since issuing its interim report, the U.S. government has joined the ITER negotiation process as recommended in its interim report.

This need was affirmed by DOE Secretary Abraham in January in a talk at the Princeton Plasma Physics Laboratory¹²:

“[O]ur 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.”

The preparation for, and execution of, a burning plasma experiment will be a multi-decade 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 effort, to progress towards the long-term fusion energy goal. These goals can only be achieved through a balancing of the program in a dynamic way.

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

1.3 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 the physical processes governing observed plasma behavior—a feature that was formalized with the 1996 restructuring of the fusion program. Successive studies and reports on the program have pointed to the science focus of the fusion program as 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 to build 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 and technical understanding in pursuit of the energy goal of the 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

¹² http://www.pppl.gov/common_pics/secretary_remarks.pdf

therefore how the DOE fusion program should be designed recognizing both this time scale 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 sections addresses the breadth of the fusion program necessary to support the development and operation of the ITER facility, and achieve a program where the critical elements are in balance to achieve the long-range program goals. In so doing the committee addresses the third element of its charge—this part of the charge asks for "An independent review and assessment for the U.S. magnetic fusion burning plasma experimental program ... 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." 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 Assessment 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, detailed in Chapter 4.

1.3.A 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.”

The program has defined three goals to achieve in pursuit of this mission¹³:

- 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.

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 these goals must evolve to reflect current program priorities. The first two elements are often referred to as the so-called “core” 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.

¹³ *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, U.S. Department of Energy, DOE/ER-0684, August 1996.

In carrying out its analysis of the fusion program, the committee has not found the common characterization of the U.S. fusion program into a “base program” and a burning plasma program to be particularly useful. The committee has found it to be 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 last decade the program has 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, improve reactor concepts, and establish the science base which 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 reviews. The advances made by the portfolio approach fusion program are documented in detail in the 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 plasmas...”

While concluding that fusion “science is on par with other fields of physical science”, the FUSAC study also noted that:

“A strong case can be made that a program organized around critical science goals will also maximize progress toward a practical fusion reactor.”

The 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. 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 ITER, it will be necessary for many existing activities to substantially refocus in support of the burning plasma ITER program. In addition the balance between science and technology activities is critical. The committee noted in its interim report:

“[A] technology program without a strong scientific 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.”

This need for a broad science program has been recognized also by the DOE Office of Science, which said in an Occasional Paper released before the decision to reenter ITER negotiations:

“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 & modeling, diagnostics, advanced & innovative concepts, and plasma & fusion technologies will be needed to ensure the success of ITER and the pathway to fusion energy.”¹⁴

The balance of the research portfolio of the U.S. fusion program has been successful and it is 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 this balance following this significant change to the program. The following discussion is framed in the context of the next few years and provides only general guidance for the rest of the decade because increased understanding of phenomena such as turbulence, transport, and magnetic reconnection are likely to change in very significant ways the course of ITER experiments.

1.3.B Primary Issues of Fusion Science Research

The pursuit of the three fusion-program goals, as detailed above, supports developing 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 de-emphasized upon the withdrawal of the U.S. 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 a specific topic, which can

¹⁴ http://www.sc.doe.gov/Sub/Occasional_Papers/6-Occ-Bringing-a-Star-to-Earth.PDF

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 fusion program is focused on innovation and optimization, based on 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 it generates. Over the last two decades, a number of methods to suppress ion turbulence were discovered, including stabilization by sheared flows. These experiments together with continued progress in theory and simulation will lead to improved predictive understanding.

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 In configurations where plasma currents dominantly produce the magnetic field, or where it is unstable due 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.

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 is therefore 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 last

twenty 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 fusion program as it pursues the program goals, it is also natural to consider what are the opportunities for the fusion program as it prepares to incorporate a burning plasma program? In particular the committee has considered in its analysis: 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? These issues are discussed below, followed by a discussion about the workforce and education issues that face the fusion program and the fusion community.

1.3.C 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 multi-decade activity. While there is every confidence that ITER will be a successful scientific endeavor, there are a number of scientific and technological issues that must be addressed to prepare for and make 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. They define a substantial part of the role 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

the body of this report. A short summary is given here.

- *Theoretical understanding and modeling* - This 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 to allow fully predictive transport models from the edge to hot core region.
- *Turbulent transport* - Understanding the transport in H-mode discharges could lead to increases in energy gain, and/or operation at reduced current and magnetic field.
- *Edge-localized modes (ELMs)* - Understanding these modes is needed to mitigating 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 prior to the initiation of ITER experiments would provide 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 alternate plasma facing components can be used to ameliorate this issue, thereby decreasing the potential for ITER downtime.
- *Disruption avoidance and mitigation* – 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 to explore alpha physics and steady state operating scenarios.
- *Plasma facing components* – This is a key issue for ITER R&D; new designs must be further developed for fabrication with large-area manufacturing techniques.
- *Diagnostic development* – Deployment of complex measurement techniques in a hostile radiation environment requires careful integration into the facility design, and 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.

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

In addition the committee considered roles for the four largest concept-optimization research programs, and below are summarized its specific scientific goals for each of these programs.

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, etc.) to provide this enhanced performance. The integration of these varied tools and characteristics into an integrated 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 (ST) The spherical torus (ST) is attained when the toroidal aspect ratio of a tokamak is reduced towards 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 fusion energy development.

Demonstrate sustainment and enhanced confinement in the Reversed Field Pinch (RFP) The reversed-field-pinch (RFP) is a toroidally symmetric configuration wherein the magnetic fields are generated mainly by internal plasma currents. These currents result in the toroidal field changing direction near the plasma edge region (hence the name). It 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). It is at a level of development considerably less mature than the tokamak.

Explore the Potential for Passive Stability and Steady-State Operation in 3-D 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. It 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 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.

Explore Novel and Emerging Fusion Science and Technology Concepts 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, can be addressed in small-scale experiments. 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 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 committee agrees that, generally, the aggregate level of activity discussed above is needed to support both the move to a burning plasma program and maintain a vibrant, productive domestic research program that is making progress on to 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 it is not meant to be proscriptive. The choice of what opportunities to pursue must be determined by the usual federal government process, advised by the fusion community as described later in this report, including consideration of the U.S. fusion program goals and international fusion activities.

1.3.E Theory, Simulation, and Computation

Transferring burning plasma knowledge 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 which

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 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 served the program well. However, significant near-term challenges remain in the areas of plasma edge physics, turbulence on transport time scales, 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 edge physics. This region, at the outer boundary of the plasma, is one of rapidly varying density and 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.

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

The role of the universities in the fusion program is many-fold. The universities train the students who will fulfill the future workforce needs of the field. They 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 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 test beds for new ideas and 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 world-wide stage, this trend—long-standard in astronomy, high-energy, 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.¹⁵ In comparison with other fields,

¹⁵ NRC FUSAC report, p. 13.

university fusion and plasma faculty members are older than their counterparts, with comparatively fewer new hires in the field.¹⁶ 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 – 60 age group.¹⁷ Meeting these personnel needs is a key function of the university fusion programs. As expressed in the committee's interim report,¹⁸ "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 post docs into the program requires that it have a strong university-based component." 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 NRC 1995 Plasma Science Study and 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 recent University Fusion Association survey of university plasma and fusion programs shows a decline of fusion science positions in the most highly ranked academic institutions in the United States. These programs tend to be the largest, most visible university fusion programs. The UFA survey of 10 of these large institutions indicates that 15 out of 66 faculty will reach retirement age in the next five years, while their institutional plans call for hiring at the very most nine faculty members over the next five 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 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 U.S. has built only one major fusion device in twenty 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%, 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 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

¹⁶ *Report on the Age Distribution of Fusion Science Faculty and Fusion Science PhD Production in the United States*, E. Scime, K. Gentle, A. Hassam, University Fusion Association, July 2003.

¹⁷ Ref. from R. Fonck, *source to be determined*.

¹⁸ BPAC Interim Report, p. 9.

a few major facilities, pushing small-scale projects aside, makes the withering of these programs a real possibility.¹⁹ Similarly, there is a danger that a concentration of theory funding for only tokamak and burning-plasma problems will lead to a drying up 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 fusion program must be the steward of plasma science in order to maintain the flow of new ideas and new talent into fusion. Although the fusion program has made important contributions to basic physics knowledge in areas such as fluids and nonlinear dynamics,²⁰ 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, plus 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 decision to join 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/NSF 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 the plasma and fusion faculty, and fusion-laboratory personnel are aging and that there may be a serious shortage in future professionals as ITER develops and the program expands. However, as OFES funding improves, this situation may become more positive. It is appropriate for OFES to initiate a review of the demographics, 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 students and post docs 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 DOE Office of Science supported facilities.

1.3.G The ITER Negotiations and Program Contingency

¹⁹ In 1985, funding for the nation's fusion-laboratories (including MIT) accounted for 93% of the OFES budget. In the year 2000, they accounted for 83% of the OFES budget.

²⁰ NRC FUSAC report, p. 72.

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. 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."²¹ The committee reaffirms this conclusion. Involvement in high-technology components is important 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.

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:

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

The committee was pleased to learn that a preliminary and successful review of the construction costs was conducted and considers this is 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 which 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

²¹ The committee notes that the text in the interim report has a comma between facility and consistent. Since publication 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 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.

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 actions recommended in its interim report (reproduced above).

Notwithstanding the good will of all 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 revisited in this context. Depending on the circumstances, 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 unavoidable scientific critical path toward fusion energy, any delays in realizing such an experiment—such as a failure in ITER negotiations—will necessarily delay the domestic program’s ability to address and understand fusion science questions necessary for practical fusion power.

1.4 STRIKING THE BALANCE

1.4.A Summary of Findings and Discussion

The fusion program, after many years of research, is poised to take a major step forward 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 a burning plasma experiment will make critical contributions to understanding fusion-science and fusion-technology issues such as; 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: confinement projections; operational boundaries—plasma pressure and current; mitigation of abnormal events; maintenance of plasma purity; characterization techniques; plasma control techniques; fabrication of necessary components; component lifetime in a nuclear environment; 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, a consensus has been built among members of the fusion community that the United States should seek to join the ITER project. Preparations for the ITER project are well advanced and the United States government began participating in the ITER negotiations from 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 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 are not complete. However, once made, fulfilling the international commitment to construct and participate in ITER 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 fusion program. This rebalancing is especially required given that finite funding resources cannot be expected to support all possible interests of the community. The new restructured program may be considered an evolutionary change from the present structure, but nonetheless will require changes across the whole fusion program.

This evolution in the program must be accompanied by the recognition of the strong inter-connection 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 an overall balanced program. The distinction between a “base program” separate from the burning plasma activity, or 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, for example.

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 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 to the level of commitment and timing required to achieve the fusion energy goal. However, the technology programs at this point will be those focused on technologies which will enable a successful burning plasma experiment, i.e., primarily those 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, there will be the need to decide 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. A discussion of the need for settings of priorities is given in the section *Setting Priorities to Strike the Balance*.

1.4.B Implications for the Fusion Community

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 has been addressed so far in this report by considering a technical level of participation. It is important for ITER participation, and indeed the entire U.S. fusion program, that the community consider changes in the way it operates to position itself to provide the intellectual leadership of chosen areas of research and 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; some examples may include elements of advanced tokamak development, stabilization of large-scale MHD instabilities, turbulence and transport studies, etc. This approach requires the organization of the community around campaigns based on scientific issues more than campaigns based on operation of individual facilities. Such an approach appears to be working well in the European program for 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 a more user-group model, and more effectively engage the research community in those 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 optimize both the large investments needed in the domestic program and give practical experience for ITER participation.

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 the community is intellectually and sociologically positioned to optimize its participation in ITER as well as optimally exploiting its domestic faculties.

1.4.C Budget Implications

As stated in the 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.” 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 ITER participation for the U.S. are just starting, it is not possible to estimate the exact level of funding needed to pursue a viable research program in ITER.

The committee is concerned about the pressures on the program as the U.S. moves into the ITER program without an increase in funding for 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 help mitigate technical risks during ITER construction. Most of the funds for ITER construction will go to those in industry who will actually manufacture components.

A flat budget for OFES will degrade the scientific research support in the fusion program, inevitably leading to decay in facilities and research opportunities. A constriction of the fusion program to pay for ITER participation will disproportionately weaken the presence of the fusion program in academia, and 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 the large national facilities will reduce critical activities the U.S. community needs to pursue to both allow significant contributions to the planning of ITER research and pursue configuration optimization. Such a reduced effort, in turn, will increase the risk of the U.S. playing a following instead of leading role in the ITER scientific program. Similar considerations are clearly relevant for theory and simulation, and technology. Overall, this approach weakens the very structures needed to optimize the benefits of the investment in ITER. A clear

example of this kind of weakening has already been set wherein much of the fusion technology program that was focused on developments beyond ITER was eliminated in the FY04 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 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 increase its connections 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 ITER 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 at \$50 million to \$100 million per year, without elaboration.

What is clear is that, at a minimum, to capture the benefits of a burning plasma experiment an augmentation of the U.S. program covering all the U.S. ITER construction 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 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 current ongoing and planned activities. The balancing process also could be guided by a multi-year 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.

1.4.D 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 including participation in ITER. 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 program. The OFES and the fusion community will have to make serious priority judgments in determining its activities at all stages of the 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. Under any funding scenario that can be reasonably expected, there will be the need to decide the relative priority of activities to pursue at any given time. As the program rebalances its priorities in light of commencing burning plasma studies, some lean years may be expected. The choice of what opportunities to pursue—including what 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.

Although active planning has been undertaken by the U.S. fusion community in recent years, the addition of so major a new element at ITER requires that 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 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 has concluded that in order for a balanced program to be developed which will maximize the yield from participation in a burning plasma project, the prioritization process should be organized with the 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;
- 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 processes in the fusion research community. Further discussion of possible models for this process, and the types of questions participants in the process might ask in the making of real priorities, are given 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 which 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 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 to ensuring the best balance of the fusion program and the continued vitality and leadership of the U.S. fusion program.

1.5 CONCLUSIONS AND RECOMMENDATIONS—ELEMENTS OF A STRATEGICALLY BALANCED FUSION PROGRAM

1.5.A Conclusions

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

The committee has concluded that the scientific and technological case for adding a burning plasma experiment to the U.S. fusion program is clear. During the last decade, the portfolio of activities within the U.S. fusion program has achieved notable advances in understanding and predicting fusion plasma performance. There is now a high confidence in the readiness to proceed with the burning plasma step because of the progress made in fusion science and fusion technology. It is also clear that progress towards 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 ITER program provides the best opportunity for the U.S. to engage in a burning plasma experiment.

Of the choices proposed for U.S. participation in a burning plasma experiment, ITER, with the U.S. 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, 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 ITER 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 ITER participation to optimize the scientific output of this investment.

Conclusion: The fusion effort requires a strategically balanced program in the context of ITER participation to optimize the scientific output of this effort and maintain its 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 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 composed of complimentary and diverse efforts. All three elements of the U.S. fusion program, outlined earlier, are essential. The committee has concluded 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 like ITER.

The outcomes of the negotiations to join ITER are critical to the future development of the U.S. fusion effort. As such it is vital 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 work through the difficult, often contentious, but vital process to prioritize all parts of the program. In the absence of such a process, budget pressures and ITER commitments can 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 in a position where it cannot 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 program will be best addressed on non-burning 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 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 upon strong programs in plasma and fusion science. Universities have and will continue to play several critical roles including maintaining the workforce supply and serving as research centers which can generate and nurture new scientific and technological ideas, and leverage extensively the latest knowledge from other fields of science.

The committee has concluded 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 further along the path to practical fusion energy.

1.5.B 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 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 ITER. If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced fusion science program.**
- **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.**
- **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 program funding will be required in addition to the direct financial commitment to ITER construction.**

- **The fusion science program should make a focused effort to meet personnel needs that 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. The prioritization process should involve significant community input and should be organized with three elements of the fusion program in mind:²²**
 - **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 .**

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 multi-year focus and must be cognizant of overall federal budgetary issues and likely spending constraints. With this in mind the committee offers some observations on the budget implications of the strategy recommended herein:

- **A funding trajectory should be developed that provides 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 program.**
- **A flat budget for OFES will degrade the scientific research support in the fusion program, inevitably leading to decay in facilities and research opportunities. Overall, this approach weakens the very structures needed to optimize the benefits of the investment in ITER.**

²² These program elements are indeed the three goals of the U.S. fusion program as outlined by DOE/OFES in 1996. The committee affirms these elements as substantive and appropriate for a strategically balanced program.

- **At a minimum, to capture the benefits of a burning plasma experiment, an augmentation of the U.S. program covering all the U.S. ITER construction and operating costs would be required.**
- **The OFES and the fusion community will have to make serious priority judgments in determining its activities at all stages of the program.**

1.6 FINAL COMMENT

The committee has concluded that the United States is ready to take the next critical step in fusion research and recommended 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.

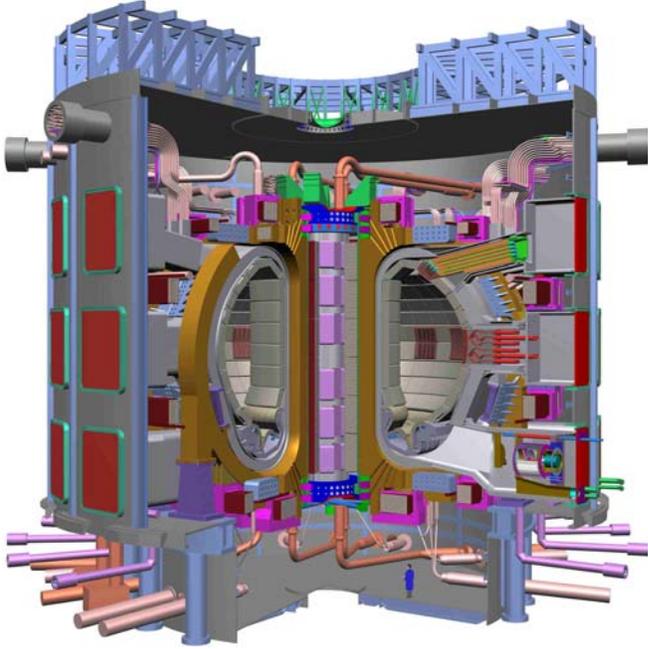


Figure 1.1. Schematic of ITER (person for scale). Courtesy of ITER.

2. Scientific and Technological Value and Interest of a Burning Plasma

2.1 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 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 fusion reactions. These early experiments were smaller and less powerful than needed to achieve the plasma confinement conditions for producing a fully burning plasma wherein more power is released by the fusion reactions than the power 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. However, 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.

However, no experiment has yet entered the burning plasma regime, and the physics in this self-heated regime remains largely unexplored. For comparison, Table 2.1 presents some critical parameters expected for a burning plasma experiment in the ITER device compared to the values achieved to date in D-T experiments. A burning plasma experiment would address for the first time all the scientific and technological questions that all fusion schemes must face. This 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 is of necessity a tokamak.

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 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. A

tokamak-based burning plasma experiment should produce scientific understanding and technological developments of general use for a wide range of configurations.

The scientific understanding of burning plasmas derived from a tokamak experiment such as ITER, if developed and understood in sufficient detail to provide predictive capability, will be transferable to other magnetic configurations. The tokamak configuration is closely related to most other leading contenders for fusion energy development, so that a wide range of phenomena may be extended to other configurations through theory and computation in the future. This includes alpha particle confinement and transport, the interaction of alphas with instabilities, fusion burn control, interactions of turbulence and MHD phenomena with alphas, etc. The degree to which theory and computation will allow extrapolation to other configurations will evolve in 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:²³

“(To) advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.”

The program has defined three goals to achieve in pursuit of this mission:²⁴

- 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.

While the study of burning plasmas will contribute to achieving the first two goals of 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 does just that by analyzing the importance of a burning plasma experiment for fusion energy sciences and the development of fusion energy, basic plasma science, 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

²³ *Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program*, U.S. Department of Energy, DOE/ER-0684, August 1996.

²⁴ *Ibid.*

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 importantly, it provides the first opportunity to test many relevant fusion technologies at a reactor scale.

2.2 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 gained. The approach to the burning plasma regime by TFTR and JET are critical examples; 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 a burning plasma experiment, due to its unique plasma parameters and its ability to study these issues in the burning state, will make critical contributions to understanding:

- Plasma behavior when self-sustained by fusion (burning);
- Plasma turbulence and turbulent transport;
- Stability limits to plasma pressure;
- Control of a sustained burning plasma; and
- Power and Particle Exhaust.

2.2.A 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 magnetohydrodynamic (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 DT 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 requires 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 is a complex and scientifically challenging problem. It will be advantageous to do so in a flexible experiment where 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 challenge to the stability boundary and allow excitation of these modes. As such, ITER will 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.

2.2.B Plasma Turbulence and Turbulent Transport

A burning plasma experiment will extrapolate our knowledge of plasma turbulence and turbulent transport from present experiments to the effective size of a full energy-producing reactor. The effective plasma size (physical size divided by ion magnetic-gyroradius) must be increased by a factor of 3 - 4 in order to achieve burning conditions, either 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. Additionally, transport studies in the regime where electron and ion temperatures are comparable (due 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 presently available, into the range required for an energy producing plasma, is necessary for developing a predictive capability of future fusion plasma performance.

2.2.C 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 sustained plasma. In tokamaks, the maximum pressure is limited by plasma instabilities. The proposed burning plasma experiment designs build upon the understanding of these instabilities developed from existing tokamak experiments, including 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. This 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.

2.2.D Controlling Sustained Burning Plasmas

A reactor should operate in steady state, minimizing the recirculating power (maximizing the energy gain). In envisioning steady-state advanced tokamak (AT) configurations, 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 non-linear and self-organized. Achieving and controlling such a self-organized plasma configuration in a burning condition will be an exciting challenge. This will require development of new diagnostics, theoretical and computational models, and feedback control methods.

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

2.2.E 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 exhaust the helium ash. For example, in ITER the total power transported out of the plasma will be about 100MW 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. ITER 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 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.

2.2.F 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 which 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 systems 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 sufficiently flexibility to modify the susceptibility to these various nonlinearities so that their respective influences on the aggregate behavior of the burning plasmas system can be reasonably isolated and tested.

2.3 SCIENTIFIC IMPORTANCE OF A BURNING PLASMA FOR BASIC PLASMA PHYSICS

Basic plasma physics is the study of fundamental processes in the plasma state of matter. This is relevant to a variety of fields, including space plasmas, industrial plasmas, astrophysics, and fusion. The burning plasma experiment is an experiment with specific scientific goals of great importance to fusion power. As such, it 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 leading to and in support of it may make

useful contributions to the basic understanding of plasmas. This section explores this possibility by considering four fundamental plasma processes that are not yet fully understood and their role in the burning plasma experiment.

2.3.A 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; sudden release of energy in heat and waves; and non-local 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 phenomena, but much is still unknown. We expect to see tearing modes, disruptions, and sawtooth oscillations in the burning plasma experiment, and 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.

2.3.B 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 minimizing turbulence is a major goal of the fusion program. Plasma turbulence also controls the behavior of accretion discs 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 H-mode confinement—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 by ions. This issue will also be addressed extensively by a burning plasma experiment and will hopefully 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.

2.3.C 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. 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 events, however, and this data will help unravel the mysteries of abrupt plasma behavior.

2.3.D 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 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 section above *Magnetic Field Line Reconnection*. Clearly, the burning plasma experiment will contribute greatly to our understanding of such plasmas.

2.3.F 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 in the previous section. 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 non-burning 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, systematic studies of any basic process are best done on the smallest or simplest laboratory devices that can access the appropriate regime.

2.4 GENERAL SCIENTIFIC IMPORTANCE OF A BURNING PLASMA

Progress in plasma physics, and fusion plasma physics in particular, leads to progress in other subfields of physical science. A burning plasma experiment would carry these applications into a new regime. There will undoubtedly be unexpected discoveries, and we mention only a few examples of these connections here.

Astrophysics and space science is replete with evidence that heat, magnetic flux, and angular momentum are transported much more quickly than predicted by straightforward physics.²⁵ Enhanced transport leads to dramatic energy release events such as solar flare, geomagnetic substorms, and x-ray emission from the vicinity of black holes. Laboratory plasma physics has already led to substantial insights into these processes based on data, theory, and advanced numerical methods. 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.²⁶

Another example 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. Examples include large-scale planetary and solar flows driven by small-scale turbulence, and 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.²⁷ 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.

2.5 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 reasons, to 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.

²⁵ *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, National Research Council, National Academies Press, Washington, DC, 2003.

²⁶ *The Sun to the Earth—and Beyond*, National Research Council, National Academies Press, Washington, DC, 2003.

²⁷ *Plasma Science: From Fundamental Research to Technological Applications*, National Research Council, National Academies Press, Washington, DC, 1995.

2.5.A 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 ~ 1m thick and is fabricated in modules designed to be remotely replaceable several times during a fusion plant's lifetime. It provides 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 need to operate at high temperature in order to optimize plant efficiency, both for plants intended to produce only electricity as well as plants that could produce both electricity and hydrogen.

The principal non-defense source of tritium is the Canadian CANDU reactors. While the Canadian supply is expected to be adequate for providing the fuel for ITER without additional breeding, any fusion reactors beyond ITER must clearly produce and recover more tritium than burned if fusion energy is to be viable.²⁸ A blanket providing this function is a critical fusion technology, and must be developed on ITER to ensure a tritium fuel supply for future fusion facilities.

A burning plasma experiment with ITER's scope provides the opportunity to evaluate the tritium-breeding ratio and extraction process, the thermo-mechanical performance, and the plasma compatibility of near-full-scale test blanket modules. In particular, the 3000-second 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 thermo-mechanical 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, i.e., 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 are well characterized and small enough that the machine's structural integrity will not be challenged. It should be noted that neither evaluation of blanket performance under fusion reactor neutron fluences nor evaluation of materials lifetime

²⁸ Any arrangement to use Canadian tritium would of course have to be negotiated between ITER and the Canadian government. Another possible source of tritium would be the targets 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 is successful.

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 to provide a means of extracting energy from the plasma, breeding required fuel, and provide shielding of external subsystems in future reactor concepts. A burning plasma experiment provides the first opportunity to test such blanket concepts.

2.5.B Tritium Processing

Most of the fuel injected in 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 re-injected as fresh D-T fuel. Elements in the fuel-processing system such as the step of separating into isotopes have already been developed at small scale. The fuel recovery system designed for ITER would operate on-line under quasi-steady-state conditions using technology that would be prototypical of that needed for a reactor. 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. Due 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 JT-60U) during the last 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 by either excluding carbon from the choice of first-wall materials or developing techniques to mitigate the formation and/or retention of these hydrocarbon films.

Control and recycling of the tritium fuel, while minimizing the tritium inventory in the plasma chamber, will be required to routinely operate a burning plasma experiment, similar to requirements for future reactors.

2.5.C Magnet Technology

The superconducting magnets required for ITER are of unprecedented size and scale, and are comparable to those foreseen to be required for a fusion reactor. Their development will not only continue the advances being made in Nb₃Sn-based magnets but could also stimulate research and development of magnets using still more advanced conductors and

cable design. Higher field, current density and temperature operation can all contribute to improving the economic projections for fusion energy.

A result of production of hundreds of tons of Niobium Tin (Nb_3Sn) superconducting strand for ITER could be the development of a world-wide industrial capacity which 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 (HEP) program. The development of about 30 metric tons of Nb_3Sn strand for the ITER EDA model coil programs in the 1990's resulted in an immediate increase in both performance and production capacity. The U.S. HEP 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 (VLHC). The extremely large-scale production of Nb_3Sn required for ITER would result in significant improvements in world-wide industrial production capacity, quality and costs lowered by high-volume production. This would directly benefit the HEP program, and 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 NMR.

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

2.5.D High-Heat-Flux Component Development

Burning plasma experiments will need to develop high-heat-flux components and in the operating phase will serve as a testbed 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 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 reactor-heat levels expected in a fusion environment.

2.5.E 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 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 would provide an integrated demonstration of their reliability and effectiveness.

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

2.5.F Conclusion

A burning plasma experiment such as ITER 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.

Table 2.1 Comparison of the design characteristics of ITER and the achieved conditions in D-T experiments to date. Note: the normalized pressure is the ratio of the average plasma pressure to the vacuum magnetic pressure at the horizontal midpoint of the plasma.

	<i>ITER</i> ²⁹ <i>Pulsed</i>	<i>ITER</i> <i>Steady state</i>	<i>TFTR</i> <i>(D-T)</i>	<i>JET</i> <i>(D-T)</i>
Radius (m)	6.2	6.4	2.5	3.0
Plasma Volume (m ³)	831	770	38	153
Normalized Pressure	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	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	10	6	0.27	0.64

²⁹ ITER Technical Basis, available online at <http://www.iter.org/ITERPublic/ITER/PDD4.pdf>

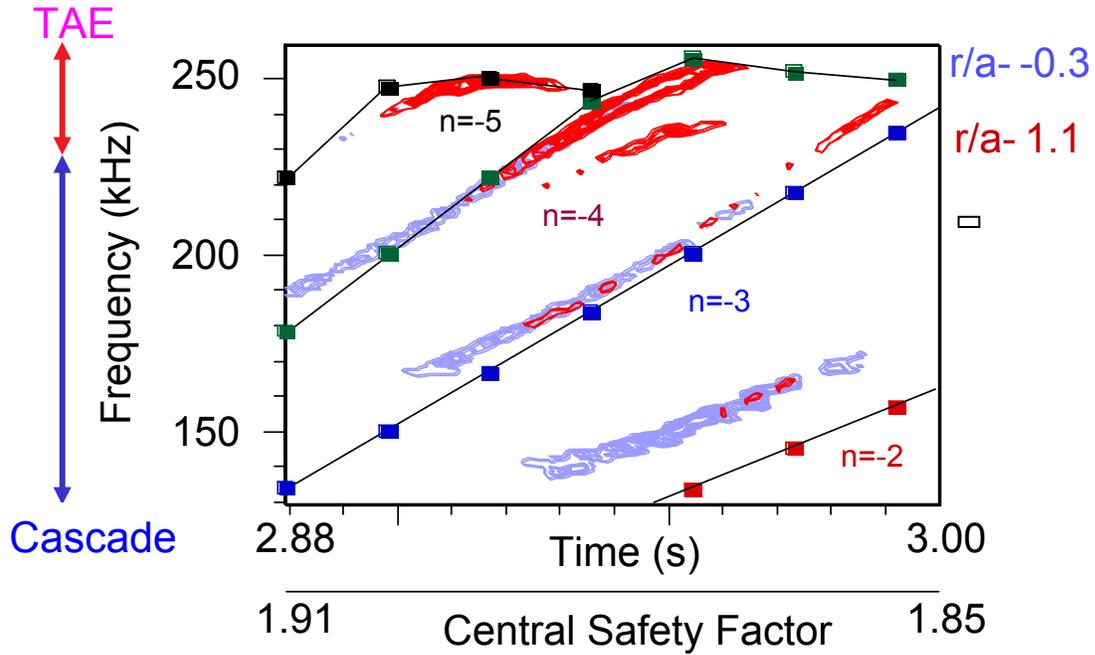


Figure 2.1 Frequency evolution of Alfvénic modes driven by fusion alpha particles in the TFTR D-T experiments, as the central plasma current evolves. Blue contours: reflectometer measurements of mode amplitude inside the plasma. Red contours: magnetic measurements of mode amplitude at the plasma edge. Squares with 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.

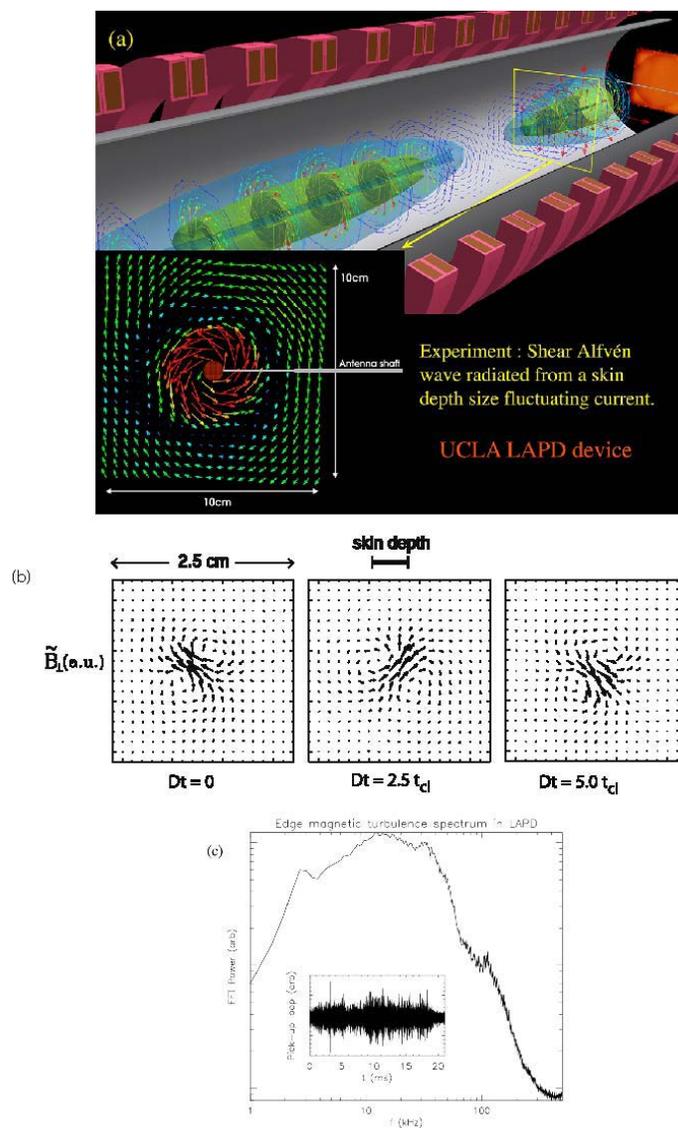


Figure 2.2 Edge plasma turbulence is composed of the superposition of many waves—a combination of both drift and shear Alfvén waves; the waves have correlation lengths on the order of the skin depth perpendicular to the magnetic field and much longer correlations along the direction of the magnetic field. 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 UCLA are shown.

(a) The measured magnetic field of a shear Alfvén launched from a fluctuating current of order of the skin depth in radius³⁰. 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

³⁰ W. Gekelman, S. Vincena, D. Leneman, J. Maggs, “Laboratory experiments on shear Alfvén waves and their relationship to space plasmas”, J. Geophys. Res., 7225-7236 (1997)

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 is superimposed on a model of the interior of the LAPD device. The wave data have been scaled by a factor of two in the radial direction for easier viewing. The insert on the lower left 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 meters from this plane. Note that the vectors switch direction along a radial cut. This is because the wave has a finite k_{\perp} , which gives them a parallel electric field.

(b) Measured magnetic field of a drift Alfvén wave, which was caused by a channel of field-aligned hot electrons with radius on order of the skin depth³¹. 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 an $m=1$ rotating spiral.

(c) Measurement of magnetic turbulence on the edge of the LAPD plasma³². 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. Turbulence is a superposition of a large number of modes as in (a) and (b) which interact with one another.

Courtesy of W. Gekelman, University of California, Los Angeles.

³¹ A. Burke, J. Maggs, G. Morales, “Experimental study of fluctuations excited by a narrow temperature filament in a magnetized plasma”, *Phys. Plasmas*, 1397-1407 (2000)

³² Data courtesy of T. Carter, UCLA

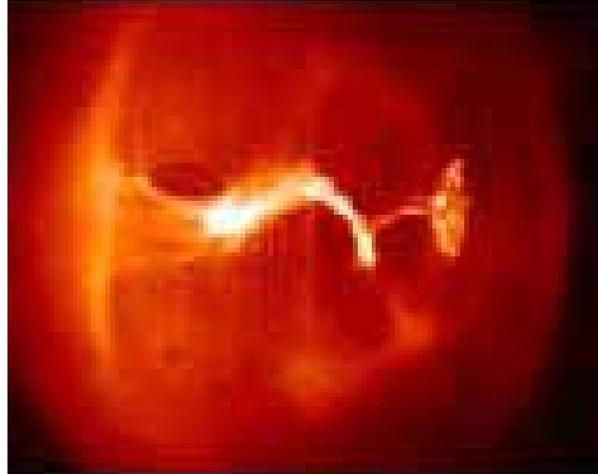


Figure 2.3 Kink instability of central column produced in Caltech spheromak formation experiment. This kink, believed intrinsic to spheromak self-organization, occurs when the jet-like central column becomes sufficiently long to satisfy the $Q=1$ Kruskal-Shafranov instability threshold. It can also be 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.

3. Readiness for Undertaking a Burning Plasma Experiment

This chapter describes the present state of readiness to undertake a burning plasma experiment. Key criteria that define scientific and technological readiness are identified and an assessment of 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 and 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 the previous chapter. 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. Satisfying these criteria effectively states that the 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 also provide significant opportunities for addressing the issues of importance to the understanding of plasma physics and physical science in general.

3.1. SCIENTIFIC READINESS

In assessing readiness, the committee found it useful to define scientific readiness in terms of six well-defined criteria. These criteria are:

- Confinement projections;
- Operational boundaries – plasma pressure and current;
- Mitigation of abnormal events;
- Maintenance of plasma purity;
- Characterization techniques; and
- Plasma control techniques.

It is the committee's judgment that each of these six science 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 to undertake a burning plasma experiment.

3.1.A 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 non-dimensional 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 ten 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 though confinement scaling studies that fit the observed energy confinement time τ_E (where τ_E is 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 three is required to go from the best confinement 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 twenty is required to reach the nominal ITER operating point corresponding to a fusion gain $Q=10$.

Scaling with similar non-dimensional parameters makes use of the fact that existing tokamaks can simultaneously match all important nondimensional parameters projected for burning plasma discharges, other than the non-dimensional 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., ITER-EDA).³³

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

³³ ITER Physics Expert Groups on Confinement and Transport and Confinement Modeling and Database, *Nuclear Fusion* **39** (12), 2175. See §7.3, p. 2211.

from the mid-size experiments in the 1980's to the present 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 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 micro-turbulence can now predict ion thermal diffusion in the plasma core. These transport models have been extensively benchmarked against experimental results.³⁴ Generally, these models reliably predict the thermal transport and the resulting core temperature profiles when provided an appropriate boundary temperature, albeit under conditions where 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, and 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 gain in the range $5 \leq Q \leq 15$.³⁵ 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, there will be discovered new (e.g., nonlinear) interactions 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.

3.1.B 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 MHD theory and can be avoided through control of the plasma pressure and current. ITER will operate within these limits and 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. An example of this MHD modeling capability is shown in figure 3.2. Such modeling helps to understand 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.

³⁴ R.E. Waltz, et al., Phys. Plasmas **4**, 2482 (1997)

³⁵ Snowmass report; J.E. Kinsey, et al., 19th IAEA Fusion Energy Conference Lyon, France, 2002, Nuclear Fusion (submitted).

Within this stable operating regime, there is another instability, called the neoclassical tearing mode, which can degrade plasma performance. This instability depends strongly on the dissipation and transport properties of the plasma. Although the theory for this instability 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.

There is a limit to the plasma density that is proportional to the plasma current and it characterized empirically. ITER plans to operate below 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.

3.1.C Mitigation of Abnormal Events

Burning plasma experiments are designed to handle safely 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 3.4). Model calculations indicate that this gas-injection technique will be applicable on the larger plasmas in ITER.³⁶ 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 edge localized modes can be avoided. However, further research and development is required, both to better understand these edge localized modes and to develop reliable methods to mitigate peak heat loads without degrading burning plasma performance.

³⁶ D.G. Whyte, et al, Phys. Rev. Lett. **89**, 055001 (2002).

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

3.1.D 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 where the ion (and impurity) confinement in the plasma core is considerably improved.

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.

3.1.E Characterization Techniques

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. Important factors include adequate diagnostic access and 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 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.

3.1.F Plasma Control Techniques

ITER has 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 burning plasma scientific issues can be addressed in this regime,

the ability to operate in high-performance regimes—the so-called “advanced tokamak” regime—will be an important step on the path to an 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, further research and development on fueling the central plasma (for pressure-profile control) and control of plasma rotation (for stabilization of resistive wall modes) is needed. Further research and development is 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 to develop techniques to feedback-stabilize resistive wall modes and to control both the electron density and electron–density profile.

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.

3.1.G Conclusion

In the last number of years there has been significant progress 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 increase our fundamental understanding of the plasma state of matter. This type of progress in fusion science and fusion technology has increased confidence in the readiness to proceed with the burning plasma step to the point the global fusion community is scientifically ready to take the burning plasma step.

3.2 TECHNICAL READINESS

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

- Fabrication of necessary components;
- Component lifetime in a nuclear environment;
- Lifetime of plasma-facing components;
- Tritium inventory control;
- Remote maintenance; and
- Fueling, heating, and current drive control.

3.2.A Fabrication of Necessary Components

The required techniques for fabricating components for ITER have been successfully demonstrated with prototypes (see Figures 3.5 and 3.6). Successful prototype components³⁷ have been built for all major systems, including full vacuum vessel segments.^{38,39} The magnet coil designs have been verified to meet the field requirements with good engineering safety margin.⁴⁰ Scenarios for remote fabrication and repair have also been tested.

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

3.2.B 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. The design of a burning plasma device must include adequate shielding for the magnetic field coils so 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.⁴¹ Further research and development is 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.

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

³⁷ Aymar, R., "ITER R&D: Executive Summary: Design Overview", *Fus Eng Design* **55**, p. 107-118 (2001)

³⁸ Ioki, K., Barabash, V., Cardella, A., Elio, F., Kalinin, G., Miki, N., Onozuka, M., Osaki, T., Sannazzaro, G., Utin, Y., Yamada, M., Yoshimura, H., "Design and Fabrication Methods of FW/Blanket and Vessel for ITER-FEAT," *Fus Eng Design* **58-59**, p. 573-578 (2001)

³⁹ Tivey, R., et al., [ADD REF.]

⁴⁰ Tsuji, H., Egorov, S., Minervini, J., Martovetsky, N., Okuno, K., Takahashi, Y., Thome, R., "ITER R&D: Magnets: Central Solenoid Model Coil," *Fus Eng Design* **55**, p. 153-170 (2001)

⁴¹ The committee notes that although ITER is presently designed with NiSn coils, existing machines and planned alternative confinement devices make use of copper-coil technology.

3.2.C Lifetime of Plasma-Facing Components

Prototype designs of plasma facing components (see Figure 3.7) have been tested for normal heat-flux conditions, and it has been demonstrated that the mechanical designs can accommodate the projected disruption forces.⁴² Both carbon-based materials and refractory metals (e.g., tungsten and molybdenum) have been qualified for fusion devices (see Figure 3.8⁴³). 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 (ELMs) 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 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, including those experienced during most disruptive discharge terminations.

3.2.D Tritium Inventory Control

Safety analyses of proposed burning plasma devices have found that all of the proposed machines meet fusion safety standards, and none require an evacuation plan beyond the site boundary. There are proven techniques⁴⁴ to separate hydrogen isotopes, clean up tritium gas, and deliver 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 ten 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. This is a key area in which further research will be required (see below).

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

3.2.E 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

⁴² Ioki, K., Barabash, V., Cardella, A., Elio, F., Gohar, Y., Janeschitz, G., Johnson, G., Kalinin, G., Lousteau, D., Onozuka, M., Parker, R., Sannazzaro, G., Tivey, R., "Design and Material Selection for ITER First Wall/Blanket, Divertor and Vacuum Vessel," J Nucl Mater **258-263**, p. 74-84 (1998).

⁴³ Figure from the Tore Supra Web-site, available online at http://www-fusionmagnetique.cea.fr/gb/cea/ts/description/ts_description02.htm.

⁴⁴ Yoshida, H., Murdoch, D., Nishi, M., Tebus, V., Willms, S., "ITER R&D: Auxiliary Systems: Tritium Systems," Fus Eng Design **55**, p. 313-23 (2001).

plasma experiment have been designed and tested. Optimization of the designs for specific burning plasma devices is continuing.

The required remote maintenance can be accomplished.

3.2.F 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 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. The choice of structural materials, insulators, and guard materials for these structures is still being optimized.

The committee finds that these criteria have now been met, except for a few remaining areas, described in Section 4.3.A, in which ongoing research is expected to adequately address these outstanding issues.

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

3.2.G Conclusion

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.

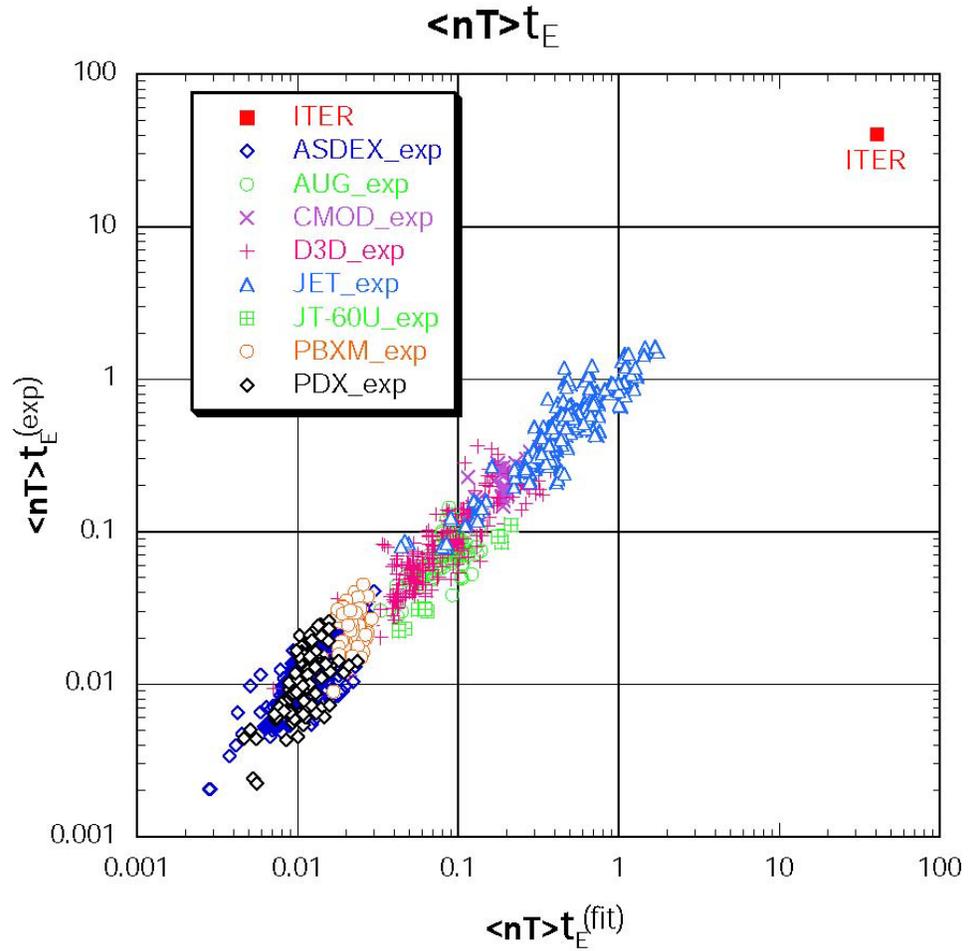


Figure 3.1 The confinement triple-product in units of 10^{20} keV-s/m³ from actual experimental discharges is plotted vs. that projected by confinement scaling studies. Data presented is taken from ITPA H-mode confinement database, the international tokamak database for enhanced confinement discharges 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. Courtesy of J. DeBoo, General Atomics, and F. Perkins, Princeton Plasma Physics Laboratory.

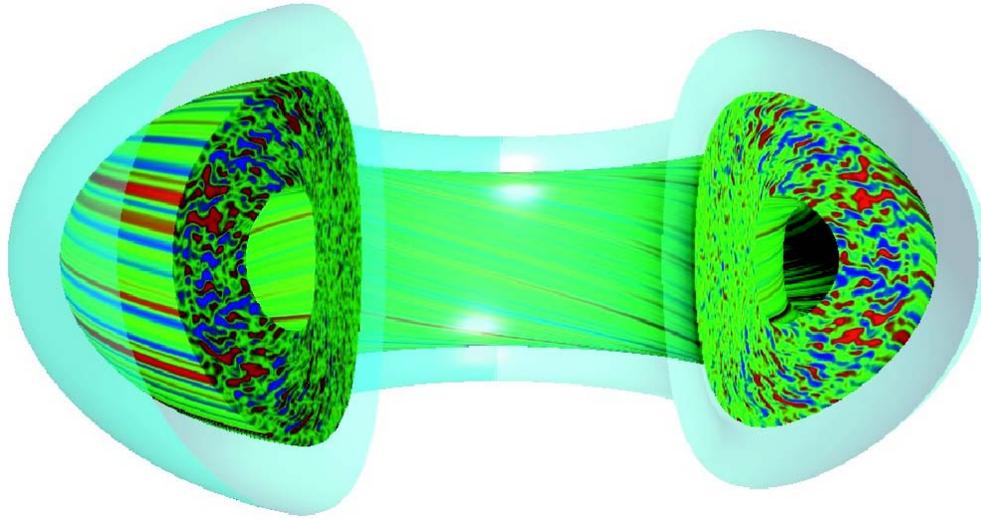


Figure 3.2. Contours of constant potential from a computer simulation of plasma turbulence in the DIII-D tokamak using the GYRO code. Note how the turbulent eddies are elongated along the magnetic field, while shear in the plasma $E \times B$ rotation prevents structures with a cross-field dimensions greater than $\sim 10 \rho_i$ from forming. Courtesy of General Atomics.

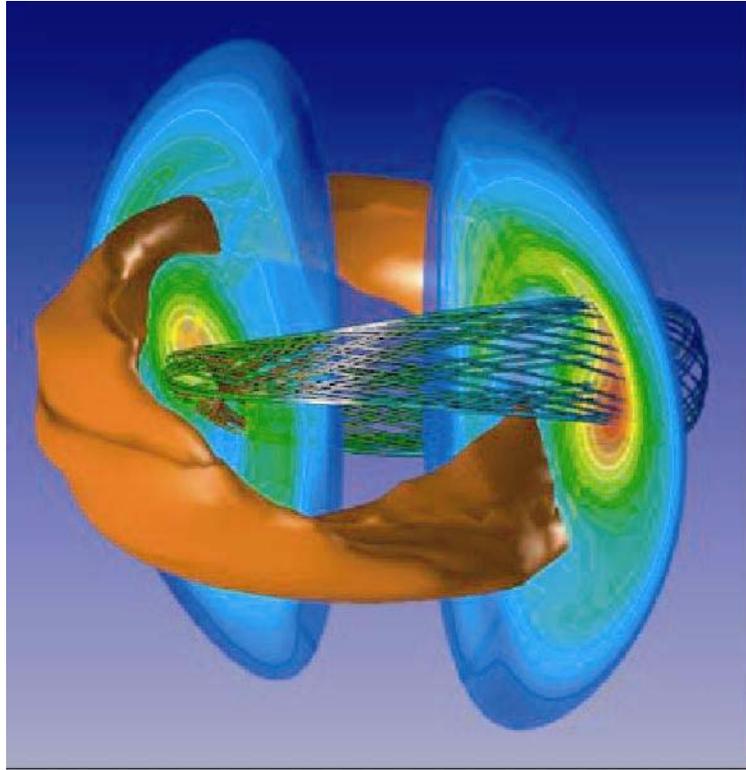


Figure 3.3 A spherical tokamak with a saturated magnetic island due to sheared toroidal rotation. Calculated by the M3D code. Courtesy of W. Park, Princeton Plasma Physics Laboratory.

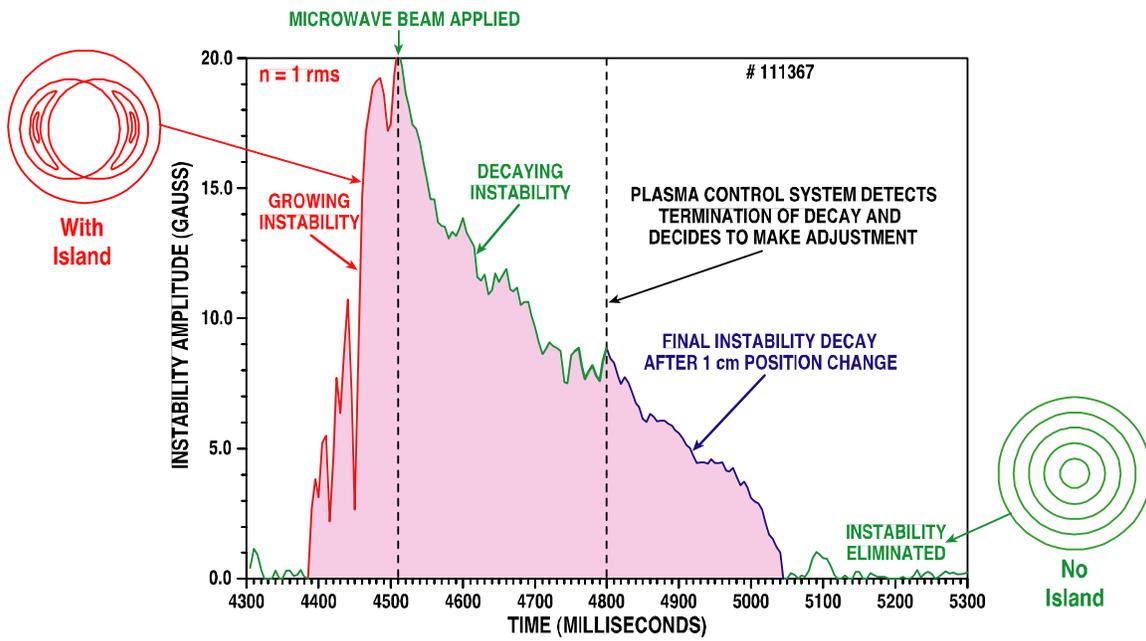


Figure 3.4 Applying and adjusting the precise position at which the microwave power is deposited stops the growth of a neoclassical tearing mode, and then eliminates it. Courtesy of General Atomics.

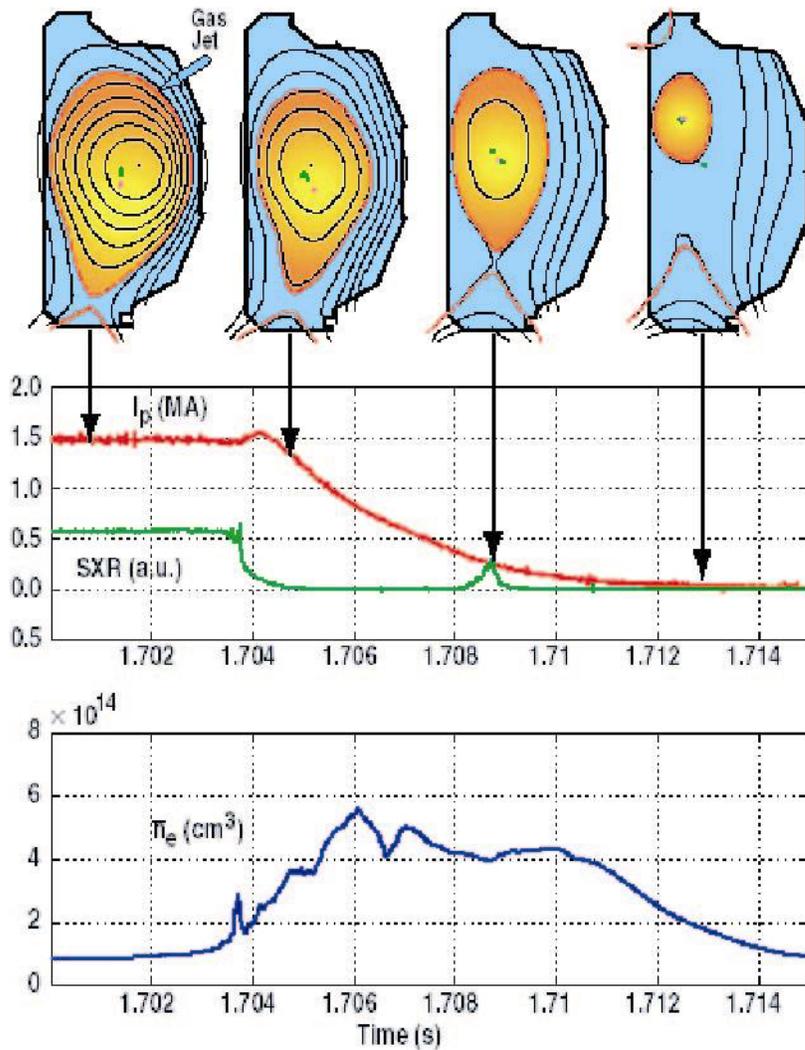


Figure 3.5. The controlled termination of a DIII-D discharge by injection of a noble gas. This technique holds great promise as a means of mitigating damage which might otherwise occur during off-normal event in ITER. Courtesy of General Atomics.

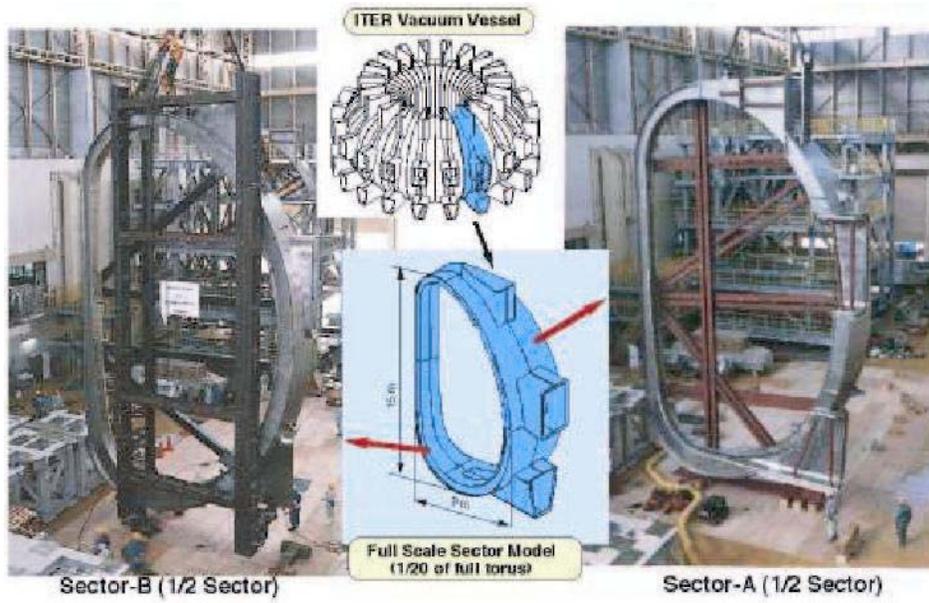


Figure 3.6 Full scale ITER Vacuum Vessel sector prototype constructed in Japan. Courtesy of ITER.



Figure 3.7 ITER Central Solenoid Model Coil that achieved 13 T and x.x T/s ramp rate (1/2 scale of full coil). Courtesy of ITER.

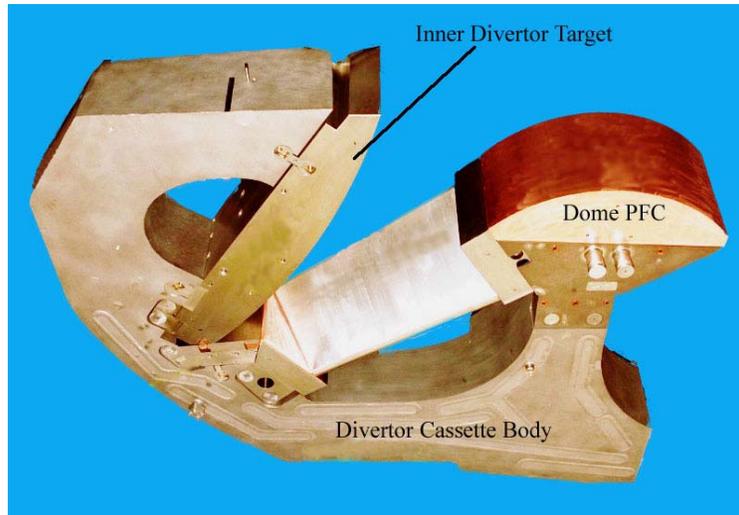


Figure 3.8 Prototype ITER Divertor Plasma Facing Component. Courtesy of ITER.

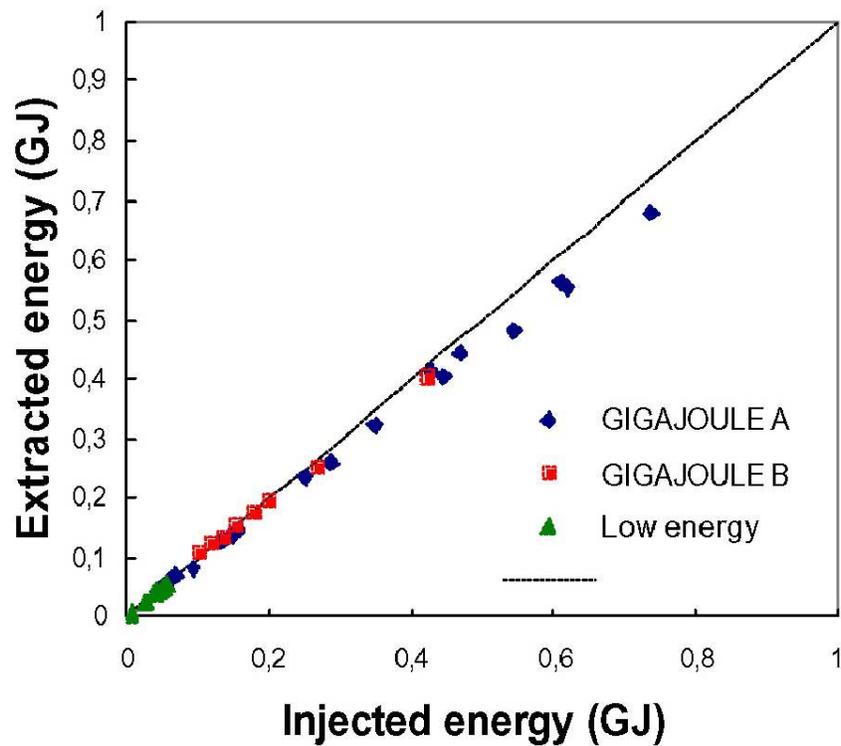


Figure 3.9 Results of experiments using an actively cooled limiter on Tore Supra. Courtesy of J. Jacquinet, Euratom-CEA Association, CEA Cadarache; Tore Supra, France; and IAEA. Ref. *Recent Developments Towards Steady State Physics and Technology of Tokamaks in Cadarache* J. Jacquinet. Proceedings of the 19th IAEA Fusion Energy Conference, Lyon, October 2002.

4. Program Structure and Balance

4.1 INTRODUCTION

It is clear from the discussions in this committee's interim report and from the expanded analysis in the earlier sections of this report, what can be learned from a Burning Plasma experiment and why the overall understanding achieved in the past decade makes a burning plasma experiment achievable. Based on these considerations, and given the centrality of a burning plasma experiment to the development of fusion energy, the committee affirmed in its interim report its recommendation that the U.S. fusion program participate in a burning plasma experiment. The committee also concluded that the best opportunity for the U.S. pursuing a burning plasma experiment is participation in the ITER project. Subsequent to the interim report from the committee, 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 have focused on addressing the first two elements of the committee's charge by discussing in detail the scientific and technical importance and the overall readiness to enter into a burning plasma experiment. This chapter addresses issues arising from the third element of the charge, which asks for "An independent review and assessment for the U.S. magnetic fusion burning plasma experimental program ... 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." The committee notes 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 Assessment Committee, and reports on the status of the various elements of the current research program, BPAC 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. A final observation to make is that because the committee's charge was limited to consideration of magnetically-confined burning plasmas, none of the inertial confinement fusion programs are considered herein.

Given that the decision to negotiate 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 will run for a decade or more. The DOE fusion program must be designed recognizing both this time scale 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 the 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."⁴⁵ The committee reaffirms this conclusion. With at least that level of participation in mind, the 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 and to maximize the scientific yield of the whole fusion sciences program including a burning plasma experiment, the committee presents in this chapter a discussion of the domestic fusion science research program. To that end, the following sections consider the outstanding compelling scientific issues facing the program—see the section *Fusion Science Issues and Research Portfolio*—and how elements of the program will address these issues—see the section *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 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 FUSAC study recommended the U.S. fusion program focus on addressing the compelling scientific issues and thereby strengthen the underlying science base of a fusion energy source. The committee agrees with this approach.

This chapter focuses on the following issues: the critical science issues to be confronted by the fusion science program, research activities which could be undertaken over the next several years to prepare for experiments on ITER, a discussion of fusion science issues to be addressed on a portfolio of smaller-scale research programs and specific goals to be pursued therein, the need for continuing efforts in theory and simulation, and consideration of education and workforce development relevant to achieving this overall program. The latter part of the chapter discusses the need for changing the structure of and setting priorities for the U.S. program in the context of a decision to proceed with a burning plasma experiment.

In formulating the rationale behind its recommendations, the committee has focused its discussion here on research elements important in the next few years and has provided

⁴⁵ The committee notes that the text in the interim report has a comma between facility and consistent. Since publication 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 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.

general guidance for the rest of the decade. The details for later years are necessarily more general because understanding of phenomena such as turbulence, transport, and stability will deepen through theory, simulation, and experiments on existing and planned facilities, and are likely to change the course of ITER and other experiments in significant ways. Plans will evolve as understanding grows, including new ideas and priorities for the experimental plan itself, new ways in which experiments are interpreted (and the tools to do this), and greater confidence with which results can be further extrapolated.

4.2 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. As noted in the program goals, 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:

- Maximize the plasma pressure,
- Maximize the plasma energy confinement,
- Minimize the power needed to sustain the plasma configuration.
- Simplicity and Reliability

The first three of these goals directly address increasing the economic appeal through 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 advanced furthest in advancing these goals and is thus capable of exploring burning plasmas. The burning plasma experiment will enable a large increment in further progress, by confronting these goals in a strongly-fusing environment for the first time.

As discussed in Chapter 2, there is a highly non-linear interaction between the plasma and the magnetic field. 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 different configurations differ primarily by the degree to which the magnetic field is controlled externally or self-organized by the plasma and plasma currents—see sidebar Magnetic Fusion Research Configurations.

The fusion program is focused on innovation and optimization, based on developing predictive understanding of the underlying physics. Accomplishing the program goals requires the investigation of the following primary 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 fusion science and technology development. It will offer exciting opportunities to study the burning plasma physics issues, as discussed in chapter 2. It is natural to ask what other activities are needed to investigate and resolve the full range of issues in fusion science? In order to maximize progress towards the goal of developing an attractive fusion energy source, how should the program be balanced between the study of burning plasmas and a non-burning program studying other critical issues of fusion science and basic plasma physics?

The proposed burning plasma experiment (ITER) is a tokamak and has been designed using the best current understanding of accessible confinement. The committee has concluded, in this report and in its interim report, that the fusion community is ready to take the burning plasma step. However, ITER is not a demonstration fusion reactor and significant further improvements are required to develop an attractive fusion system—including increased plasma pressure, efficient stable sustainment to steady state, and higher generated fusion power density. The order of improvements needed can be estimated by comparing the ITER design with the ARIES reactor studies of projected attractive fusion energy systems. The ARIES studies assume significant progress on each of the issues above to achieve higher performance than has been demonstrated experimentally, and 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 and ARIES-AT studies, where 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 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 fusion program today is pursuing several research avenues to understand the outstanding and compelling scientific issues, pursue the goals of the program, and thereby achieve these kinds of 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 research 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 and 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 has been discussed in Chapter 2—see *Scientific Importance for Fusion Energy Science and the Development of Fusion Energy*.

4.2.A 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 it generates. Over the last two decades, a number of methods to suppress ion turbulence were 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 edge transport and its influence on energy.

New magnetic configurations have been designed to facilitate suppression of ion turbulence, building on improved understanding. In the advanced tokamak and stellarator, “reversed” or weak shear of the magnetic field 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 understanding plasma turbulence will enable better configuration designs.

4.2.B 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—including a highly elongated and triangular plasma shape, modifications of the plasma current or magnetic shear profiles, and 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 the reversed-field pinch have not been experimentally observed. Experiments are underway to search for these limits and compare to theoretical predictions. In stellarators, however, the achieved pressures already significantly exceed theoretically predicted instability thresholds and improved non-linear models are being investigated. New experiments, designed using current understanding, will explore the theory at higher pressure levels and assess access to attractive normalized pressures. The experimentally-observed normalized pressure in RFPs is already high enough (~10 percent) to motivate investigation of that configuration.

4.2.C Stochastic Magnetic fields and Self-Organized Systems

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

The magnetic topology can also change due to local magnetic reconnection. This is being investigated in several research groups in a concerted attempt to understand the fundamental mechanisms. 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 that 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 is now partially understood. The experimental effort is complimented 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 that 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.

4.2.D 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 plasma flow in the toroidal direction. Theoretical studies in the 1980s demonstrated that good 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 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 attractive fusion systems.

4.2.E Control of Sustained High-Pressure Plasmas

Steady-state operation greatly increases the economic appeal of fusion systems. Efficiently sustaining and controlling high-pressure plasmas is therefore a critical issue. Toroidally symmetric configurations—including the tokamak, spherical torus, and RFP—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 will decrease 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 robustly compatible with steady-state operation, as the magnetic configuration is

maintained as long as the coils are energized. Theoretically, the pressure limit 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.

4.2.F 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 last twenty 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 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.

4.3 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 address and activities to pursue. The previous section considered the non-burning 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. For instance; 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? With these kinds of questions in mind, a range of opportunities for fusion science research over the next decade or so is presented here.

This is not the first effort to demonstrate these opportunities. The recent Integrated Program Planning Activity and Snowmass Studies, by the fusion community itself, have described challenges and research opportunities for non-burning plasma fusion science. The DOE Integrated Program Planning Activity plan⁴⁶ for the fusion program is organized around a detailed set of scientific issues and objectives. Together, these discussions established a range of science and technology goals for the fusion science program for the next 5 to 15 years.

⁴⁶ *Integrated Program Planning Activity for the DOE's Fusion Energy Sciences Program*, December 2000; available online at <http://vlt.ucsd.edu/IPPAFinalDec00.pdf>. This plan established objectives at five-year intervals, with detailed objectives for 2005, and envisioned a review at approximately that time.

From an examination of these 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 is recommended for the domestic fusion science program. Note that this list is strictly representative and it is not meant to be exhaustive. The actual choice of what opportunities to pursue must be determined by the usual federal government process, advised by the fusion community as described later in this report, including 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 to support both the move to a burning plasma program and maintain a vibrant, productive domestic research program that is making progress on to the long-range goal of establishing the knowledge base for fusion energy.

4.3.A Directly Support the Burning Plasma Program on ITER

ITER is a tokamak confinement device, and 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 multi-decade activity. While there is every confidence that ITER will be a successful scientific endeavor, there are a number of scientific and technological issues that must be addressed to prepare for and make best use of a burning plasma experiment. In this section, key areas in which ongoing U.S. research and development can make significant contributions are identified, 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. Work is needed to develop a first-principles theoretical understanding of this phenomenon.
- ***Edge-localized modes (ELMs)*** The pedestal height in the H-mode is limited by so-called edge localized modes (ELMs) that 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 presently 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 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 3.4⁴⁷. Techniques to quickly and reliably determine the location of these instabilities and control the feedback current must be developed to expand the ITER operating regime to higher pressure.
- ***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 prior to the initiation of ITER experiments would permit more effective use of ITER. “Hybrid” operating scenarios are being considered 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 is observed that is proportional to the plasma current. 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 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 permit operation at reduced values of plasma current and magnetic field. Understanding plasma turbulence is a key unsolved problem and one of the grand challenges in plasma physics. There has been exciting progress in this area over the last 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, which 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. Similar efforts are underway for turbulence in the important plasma edge

⁴⁷ R. J. LaHaye, et al., Phys Plasmas **9**, 2051 (2002); G. Gantenbein, et al., Phys. Rev. Lett **85**, 1242 (2000).

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 co-deposition tritium-laden carbon could make unusable much of the tritium inventory. Currently, two approaches are being pursued to address this issue. One is to better understand the erosion, transport, and re-deposition of carbon, and devise mechanisms to remove the tritium from co-deposited carbon. The second 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 in this is needed before DT plasmas are studied in ITER.
- ***Disruption avoidance and mitigation*** Disruptive plasma terminations can occur as a consequence of exceeding 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.⁴⁸ Further research will extend the applicability of these results to larger devices. A related issue is determining safe limiting values for the plasma operating parameters. Reliable triggers are under development to initiate disruption mitigation in the case of an unexpected event.⁴⁹
- ***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 verify that these techniques are reproducible and reliable. This research and development should be done in the approximately five years before the components are fabricated.
- ***Diagnostic development*** ITER calls for a sophisticated set of measurement techniques, capable of surviving in a hostile radiation environment. More diagnostic design is needed to integrate diagnostics into the ITER plan, while maintaining the shielding requirements within the ports. Engineering research and development is needed to ensure the reliability of materials—ceramics, optical and insulating materials—and components—bolometers, probes, mirrors and shutters—in the ITER radiation environment. New measurement techniques must also be developed, such

⁴⁸ D.G. Whyte, et al, Phys. Rev. Lett. **89**, 055001 (2002)

⁴⁹ D. Wroblewski, et al., Nuclear Fusion **3**, (1997); D. G. Whyte, et al., J. Nuclear Mat. **313-316**,1239 (2003).

as a method 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 ITER. 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 accurately predict breeding performance. It would be advantageous to start R&D on the test blanket module immediately after the ITER negotiations are completed.

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

The following sub-sections address the role of the four largest concept optimization research programs, and summarize specific scientific goals for each of these.

4.3.B 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. It is a leading candidate for a first-generation design of a fusion reactor. The AT employs active control of accessible plasma profiles (e.g., heating, density, pressure, etc.) to provide this enhanced performance. The integration of these varied tools and characteristics into an integrated 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 investigating wider ranges of plasma shape and stability limits to test the fundamental understanding of possible AT regimes.

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

- *Demonstrate integrated advanced tokamak scenarios with current sustained dominantly by the bootstrap current and enhanced confinement at high pressure, and develop predictive understanding of their accessibility and control;*

- *Develop techniques to control plasma current, pressure, flow, and transport profiles while maintaining plasma stability in this highly non-linear self-organizing regime;*
- *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;*
- *Test theories of MHD instability control and develop techniques to allow active avoidance of unstable boundaries from resistive wall modes and neoclassical tearing modes; and*
- *Demonstrate techniques to ameliorate the effects of abrupt plasma disruptions if boundaries are breached.*

4.3.C 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 towards 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 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 fusion energy development 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 to:

- *Test theory of MHD stability at conditions of extreme toroidicity 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;*
- *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;*

- *Explore the interactions of strongly supra-Alfvénic energetic particles and MHD instabilities such as the Toroidal Alfvén Eigenmodes with different spectral characteristics than found in tokamaks;*
- *Extend the understanding of plasma edge instabilities and transport to regimes of high particle trapping and strong field line expansion; and*
- *Demonstrate plasmas dominantly sustained by the bootstrap current, and initiated without an internal transformer.*

4.3.D Demonstrate Sustainment and Enhanced Confinement in the Reversed Field Pinch

The reversed-field-pinch (RFP) is a toroidally symmetric configuration wherein the magnetic fields are generated mainly by internal plasma currents. These currents result in the toroidal field changing 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. It 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). It is at a level of development considerably less mature than the tokamak, and several areas of investigation are required to evaluate its potential for fusion and provide laboratory tests of self-organizing plasmas with relevance to astrophysical phenomena.

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

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

4.3.E 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. It 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 that 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 to:

- *Test theory of MHD stability boundaries in 3-D plasmas, varying the contribution from plasma currents, and explore the sensitivity of the plasma pressure stability limit to strong 3D shaping;*
- *Test the understanding of current-driven disruptive instabilities in stellarators;*
- *Demonstrate the predicted ability to achieve tokamak-like confinement properties in stellarators with magnetic symmetry;*
- *Test theories of turbulence-driven transport in 3D magnetic configurations of varying symmetry; and*
- *Explore the ability to access improved confinement regimes in stellarators—the strong rotational damping is drastically reduced in stellarators with symmetry, and provides a test of the mechanisms of turbulence suppression.*

4.3.F Explore Novel and Emerging Fusion Science and Technology Concepts

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, can be addressed in small-scale experiments. 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 Li metal walls. Many

of them are small enough to reside in university laboratories, and thus efficiently contribute as workforce recruitment and training facilities as well as research devices.

One class of such investigations address configurations with spherical external topology 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 are susceptible to large-scale MHD instabilities. Fusion science research opportunities in this area include: the exploration of stability and confinement characteristics of spheromak plasmas in the regime where the electron collisional path length is comparable to the plasma dimensions; understanding 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, among others: the study of high-pressure plasmas in a simple magnetic-dipole configuration; the use of 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.

4.3.G 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 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. In collaboration with international partners, there are opportunities for the U.S. program 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.

4.3.H Partner with International Collaborators

It is important to recognize that research and development in the U.S. fusion program needs to be coordinated with our international partners and the ITER process. The tokamak programs are already loosely integrated with equivalent and larger facilities in the EU and Japan through the Integrated Tokamak Program 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 are also pursuing many of the issues discussed above.

The stellarator, ST, RFP, and the tokamak programs all have IEA agreements for international coordination and collaboration. Each of these respective communities hold regular meetings. In all of these cases, there is a high degree of personnel and tool sharing between the U.S. and non-U.S. programs. The U.S. support of ITER and the whole 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 optimize the return from the investment in ITER. Increased international interactions could also benefit the configuration optimization research programs, and should be strongly encouraged.

4.4 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 ITER, it will be necessary to develop a first-principles understanding of the phenomena which 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.

The progress of fusion science has relied heavily on the development of theory and extensive numerical computation and simulation. It has been recognized that the complexity of the 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) that allowed a piecemeal simplification of the complex physics. This approach has led to a new level of understanding and served the 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 ITER. 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 time scales, 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 edge physics. This region, at the outer boundary of the plasma, is one of rapidly varying density and strongly influences stability. An understanding of this region is necessary for a proper treatment of turbulence and determines diverter design. It is not adequately treated in the current simplified models. This defect stems from the need to deal with a kinetic-theory description where the mean free paths vary dramatically, where spatial gradients are large, where boundary-condition fixation is essential but often incompletely known, and where 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 in dealing with large problems as improvements in hardware. Since many of these developments are expected to arise from university-based research programs, these activities require continued support. New insights and algorithms will emerge from these efforts that will improve the simulations that will eventually have to be done on the largest of the supercomputers. One daunting goal is the development of integrated programs which 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 dependant on computation, have developed tools that can be adopted for present purposes. 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 a successful in permitting widely separated research groups to utilize common models as well as provide a test bed 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 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, etc. and combines physics of different characteristic timescales.

4.5 WORKFORCE READINESS

In the era of a burning plasma experiment, the recruitment, training, and retention of scientific and technical talent is 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. With the preparation for ITER and the execution of its experimental program expected to cover more than two decades, the technical personnel activities associated with this effort must be sustained and ongoing. Any increased U.S. investment in fusion in the era of a burning plasma experiment makes the development and maintenance of first-rate personnel in plasma and fusion scientific and engineering even more important than it has been up until now. Training the plasma and fusion workforce has two related components: broad university education in basic science and engineering, and more specialized training in technical areas specific to fusion and the burning plasma experiment.

4.5.A 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- 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 FUSAC report also noted that nation's fusion and plasma science programs

are concentrated in relatively few universities. Responding to the FUSAC and earlier studies, the Office of Fusion Energy Sciences took important actions that 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, and several small-scale experimental programs via the Innovative Confinement Concepts activity. It also took a leading role in creating the DOE/NSF program in basic plasma physics. In view of the need for supplying a sufficient workforce as the program enters the burning program era, these issues are briefly revisited here.

The rate of plasma and fusion Ph.D. production is summarized in Figure 4.3.⁵⁰ The production rate of Ph.D.'s in plasma and fusion science shows a steady decline since the mid-1980's. The decline shown in Figure 4.3 generally tracks, but starts approximately 3 years after, the onset of a similar decline in the funding level of the U.S. Fusion Energy Sciences Program. In contrast, the rate of Ph.D. production over all fields of physics shows no such decline, consistent with an approximately constant funding for physics as a whole. While a flattening of the fusion budget over the past several years offers the possibility that the fusion Ph.D. production will soon flatten, or even rise in response to the increased number of university research initiatives started in the past decade, 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 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 and diverse approaches to fusion problems. Likewise, not all students who do Ph.D. research in plasmas and fusion pursue careers in fusion. To first approximation, it is estimated that these two fluxes tend to cancel one another, although hard data is not presently available.

The age distribution of U.S. fusion science faculty as compared with physics faculty in all fields is shown in Figure 4.4. The ratio of faculty in the 55-75 age bracket to faculty in the 30-50 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 UFA report, "Hiring trends at (these) larger institutions suggest that recent and projected fusion science hiring at larger institutions is down the 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."

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 MIT—is similarly skewed toward older ages. Replacing this

⁵⁰ *Report on the Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States*, E. Scieme, K. Gentle, A. Hassam, University Fusion Association, 2003.

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 is aging markedly and 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 ITER will be near the end of their careers. While predictions over the long range are uncertain in that they depend on overall program development, it is clear that the situation merits deeper investigation and continuing scrutiny to insure a sufficiently large, high-quality workforce in the fusion science program.

4.5.B Recruitment and Basic Scientific and Technical Education

At least two factors affect the recruitment of new personnel. 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 continued expansion of outreach efforts 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 go preferentially to where there are exciting opportunities. In other words, new initiatives and sustained efforts attract talent. Given the time lag of from five to seven years from the time new initiatives are started to the time when the first students finish 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, ITER could provide just 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 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 include 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 presently undergoing dramatic changes include 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 coming 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 recruiting new talent, providing broad training of fusion scientists and engineers, expanding the ties between the fusion community and other areas of science technology research, and 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 fusion program should make a focused effort to analyze and address personnel needs required for: (1) revitalization of the fusion workforce; (2) building a burning plasma device; and (3) conducting burning and nonburning plasma experiments (see section entitled *The Role of the Universities: Research, Education, and the Fusion Workforce* in Chapter 1). If a need is found, the fusion program could consider several possible actions that would aid in accomplishing this goal. 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 Fusion Energy Sciences fellowships at the national fusion facilities could encourage graduate student participation 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,⁵¹ and the Fusion Science Center Program that is scheduled to begin with a first center in FY2004.

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.

4.5.C Specialized training in fusion technology

Fusion- and plasma-physics of the future, and particularly the burning plasma experiment, will be a highly specialized technical endeavor. In many areas, the

⁵¹ The NSF/DOE Initiative is currently funded at a level of \$4M per year. The 1995 NRC Plasma Science Study recommended establishment of this program at \$15M per year, and the NRC FUSAC report endorsed this recommendation.

traditional Ph.D. 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 on both the burning plasma experiment and 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 been only one, modest-size, fusion device built in the past decade has led to a critical shortage of trained fusion engineers. While the research and development effort associated with the ITER Engineering Design Activity helped bridge this gap, U.S. involvement in this activity ended five years ago. The fusion environment presents unique and challenging technical problems, such as 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. This harsh and demanding environment requires training personnel with highly specialized skills, capable of developing practical engineering solutions and affordable components for the burning plasma experiment.

The bidding process for the ITER work packages is now underway. It nominally requires proven experience in the technologies and devices being bid. Due to the recent de-emphasis of fusion technology, the U.S. does not now have the desired level of proven experience in most areas. As shown in Figure 4.6, personnel involved in fusion technology research and development in the U.S. have declined by about 50% since the mid-1990's, along with the budget for. While specialized facilities at universities and national laboratories have been constructed for technology research, they are currently underutilized. If the U.S. is to make the most of full partnership in the ITER activity, significant new activity must be supported to reinvigorate the U.S. fusion-technology enterprise and to enable the U.S. to participate effectively in the construction of components for ITER. It will also help to position the U.S. to play a leading role in the follow-on steps to useful fusion energy.

The fusion program could consider creating internships in fusion technology for established scientists and engineers in order to jump start the training of new fusion personnel. It could also consider increasing its involvement in industries that provide fusion-relevant technology. Such an increased involvement could benefit the discovery of new technology—developments that 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 foreseeable future. This will require increased outreach to talent pools and making increased connections to the broader academic, scientific and technical communities. It will require immediate attention to training and retaining fusion engineers capable of designing and building the many intricate components necessary for a 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 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.

4.6 PROGRAM STRUCTURE AND ITS EVOLUTION

Considering the discussions earlier in this chapter and in Chapter 3, the committee believes it is clear that in order to look at the broad range of fusion science issues the U.S. fusion program needs to both support the study of burning plasmas and a portfolio of non-burning plasma smaller-scale research efforts. These two thrusts are tightly intertwined, 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 ITER, but also to continue to look toward the larger goal of developing the foundations for fusion energy.

This need for a U.S. fusion program which pursues burning- plasma studies and addresses science issues beyond the burning plasma experiment itself has been affirmed by the Snowmass study, FESAC reviews, and outside reviews of the U.S. fusion program. 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 plasmas..."

While concluding that fusion "science is on 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. As noted previously in this report, this committee reaffirms these findings as guiding principles for embarking on a burning plasma experiment.

The initiation of burning plasma experiments on a large facility will impact all levels of the program. ITER, or indeed any burning plasma experiment, represents a significant new commitment by the U.S. 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 fusion program.

The discussion in this section addresses the breadth and structure of the fusion program necessary to support the development and operation of a burning plasma experiment on ITER, and achieve a program where the critical elements are in reasonable balance to achieve the long-range fusion goal. It is difficult to be precise now about the scale and distribution of the program elements since the negotiations that will define the U.S. commitment to ITER are not complete. Nevertheless, some general principles are clear and are presented below to define the structure of a fusion program including a burning plasma facility.

4.6.A Present Structure

When considering the distribution, or balance, of activities in the fusion research program, it is instructive to examine first the present structure of the fusion program, which was defined by the program restructuring in the mid 1990's. The goal of the U.S. fusion program is to develop the scientific and technological knowledge base for practical fusion energy production. This 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." 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."

Pursuing all three goals supports developing 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 de-emphasized upon the withdrawal of the U.S. 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 tokamak 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 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 budgetary constraints, and the withdrawal of the U.S. from the original ITER consortium, several internal (FESAC and Snowmass) and external (SEAB, Knotek) reviews endorsed this program structure and strategy.

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

A second feature of the present program is some separation 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 Innovative Confinement Concepts program and located on campuses. The larger facilities at the national laboratories generally pursue research activities that are driven as directed programs staffed mainly by laboratory staff and full-time, on-site collaborators from other laboratories and universities.

4.6.B Required Elements of a Balanced Program

Recognizing the need to optimize the scientific output of all elements of the resulting program, the distribution of activities among the elements of the U.S. fusion program must be substantively reconfigured with a commitment to a burning plasma experiment. This rebalancing is especially required given that finite funding resources cannot be expected to support all possible interests of the community. The new restructured program may be considered an evolutionary change from the present structure, but nonetheless will require changes across the whole fusion program.

One change urgently needed in the fusion community is the recognition, and integration into program planning, of the strong inter-connection 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 an overall balanced program. The distinction between a “base program” separate from the burning plasma activity, or 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, for example,

The committee agrees that the rationale for a vigorous 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 to maintain support.

The issue is then 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 suppressing activity in one area or another, as occurred when the pursuit of a burning plasma experiment was halted in the late 1990's.

As the U.S. 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 continues the evolution of the fusion program to a smaller number of larger scale experiments— but still small compared to 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, including the optimal role of universities and laboratories, priority setting, the role of technology, etc.

A large portion of the program efforts will focus directly on the burning plasma experiment as a centerpiece of the program, but the actual level of effort there 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 will be settled as the negotiations proceed. A 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 and 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 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 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, which these smaller tokamak experiments and theory can address in support of a burning plasma experiment, were discussed earlier. All 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 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.

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 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 to the level of commitment and timing required to achieve the fusion energy goal. However, the technology programs at this point will be those focused on technologies which will enable a successful burning plasma experiment, i.e., primarily those 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, there will be the need to decide 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. A discussion of the need for settings of priorities is given in the section *Setting Priorities to Strike the Balance*.

4.6.C Integration of Program Activities

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

It is reasonable to assume 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 focused on particular topical areas of high scientific interest need to be organized, comprised of researchers from all parts of the community. Organizing these teams quickly would help inform the U.S. negotiators on desired participation areas, and prepare to for ITER research. These collaborative teams would provide the focus for concentrating national expertise to be in a position 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, etc. This approach requires the organization of the community around campaigns based on scientific issues more than campaigns based on operation of individual facilities. Such an approach appears to be working well in the European program for operation of JET.

Another important element of this approach is the need to employ the technological means and develop the sociological infrastructure for large-scale program participation 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, etc.

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. 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 a more user-group model, and 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 to be effective, the large domestic facilities will need to support collaborative teaming through 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. This will optimize both the large investments needed in the domestic program and give practical experience for ITER participation.

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 the community is intellectually and sociologically positioned to optimize its participation in ITER as well as optimally exploiting its domestic facilities.

4.7 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 including participation in ITER. 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 program. The OFES and the fusion community will have to make serious priority judgments in determining its activities at all stages of the 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 situation 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 has concluded that in order for a balanced program to be developed which will maximize the yield from participation in a burning plasma project, the prioritization process should be organized with the 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;
- 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 processes in the fusion research community.

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

1. What is the priority of current programs relative to the emerging requirements associated with ITER participation?
2. What is the future for U.S. tokamak research programs? What are the priorities?
3. What should be the scope, pace and composition of the alternative and innovative configurations investigations? 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. 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 process could follow the model of the budget planning and prioritization process used by the DOE High Energy Physics Advisory Panel (HEPAP). The HEPAP process has provided important input to DOE in the process of transitioning ongoing research programs and facilities as new initiatives were implemented. The implementation of such a process will go a long way to ensuring the best balance of the fusion program and the continued vitality and leadership of the U.S. fusion program.

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 U.S. The global fusion effort is moving towards 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.

SIDEBAR: 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 decreasing degree of self-organization of the plasma configuration, see Figure 4.1. It includes the Field Reversed Configuration, the Spheromak, and the Reversed Field Pinch, all of which explore low-magnetic-field plasma configurations that rely on strong self-organization of plasma currents. They 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. These devices 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. They 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 β . Compared with a tokamak it would not require current drive; however, the internal floating ring provides a technical challenge. More details on these various concepts are available in Appendix F.

Table 4.1 Comparison of the characteristics of ITER and the ARIES-RS and ARIES-AT studies. Note: the normalized pressure is the ratio of the average plasma pressure to the vacuum magnetic pressure at the horizontal midpoint of the plasma.

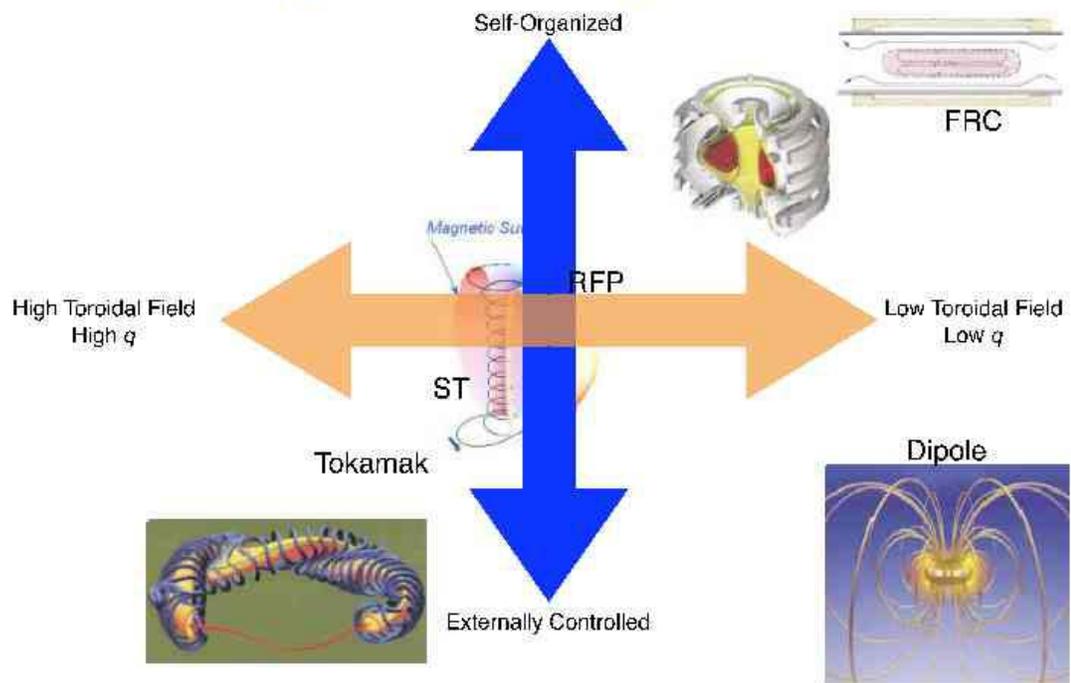
	<i>ITER</i> ⁵² <i>Pulsed</i>	<i>ITER</i> ³² <i>Steady state</i>	<i>ARIES-</i> <i>RS</i> ⁵³	<i>ARIES-</i> <i>AT</i> ⁵⁴
Radius (m)	6.2	6.4	5.5	5.4
Plasma Volume (m ³)	831	770	351	329
Normalized Pressure	2.8 %	2.8 %	5 %	9.2 %
Normalized Confinement ($H_{98y,2}$)	1.0	1.6	1.5	1.8
Pressure-driven Current Fraction		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	10	6	22	49

⁵² ITER Technical Basis, available online at <http://www.iter.org/ITERPublic/ITER/PDD4.pdf>.

⁵³ 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>.

⁵⁴ 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>.

Magnetic Configurations



NRC BP (Mane)

17

Figure 4.1 Comparison of the main experimental configurations for magnetic-fusion research. The various configurations are shown in a space defined by the level of organization and the strength of the toroidal field. Courtesy of

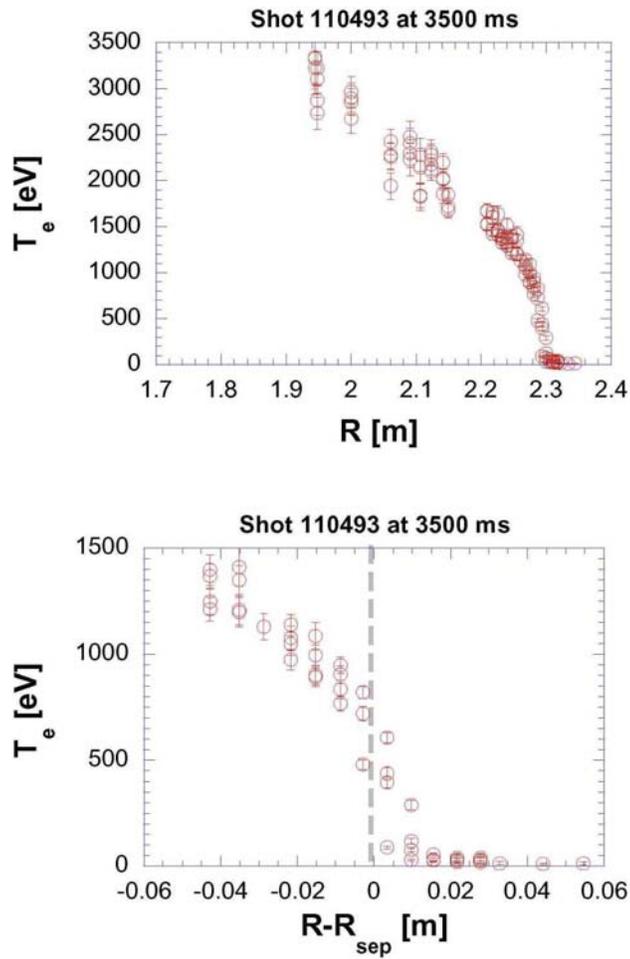


Figure 4.2 Temperature pedestal from an H-mode discharge in the DIII-D tokamak. The increase in T_e across the last 4 cm at the outboard mid-plane is comparable to the central density temperature. Courtesy of General Atomics.

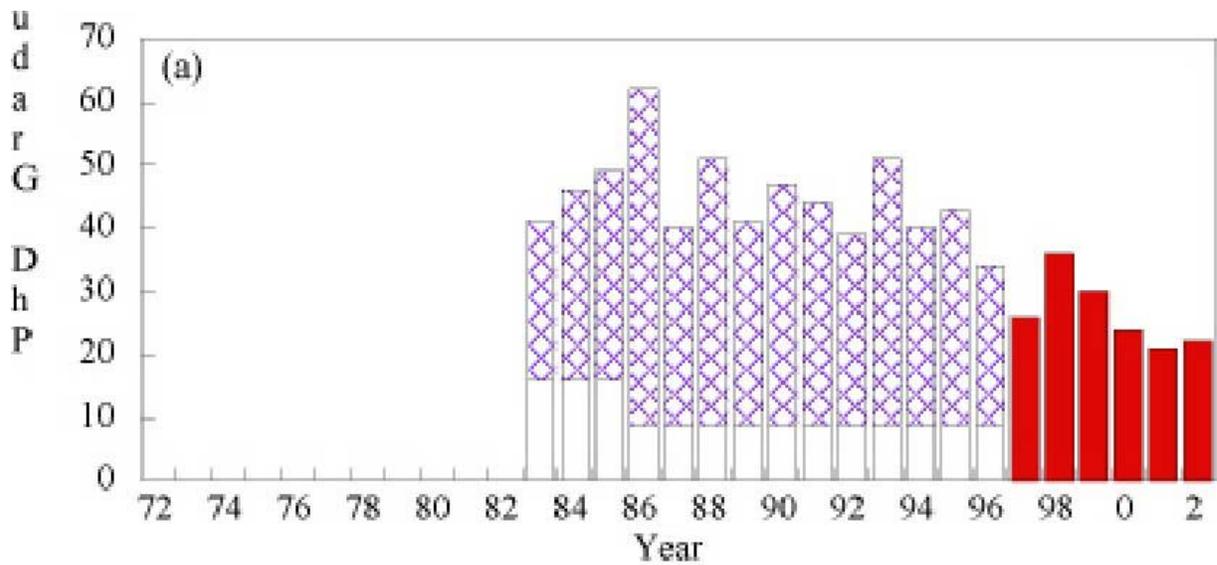


Figure 4.3. Total plasma science Ph.D. production per year from 13 institutions with major plasma science programs (red and cross-hatched) over the last 20 years shows a decline of approximately 50% in the past decade. Data from 1997 onward (shown in red) includes all responding institutions. Pre-1997 data from some institutions is incomplete. The cross-hatches show 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. Courtesy of the University Fusion Association.

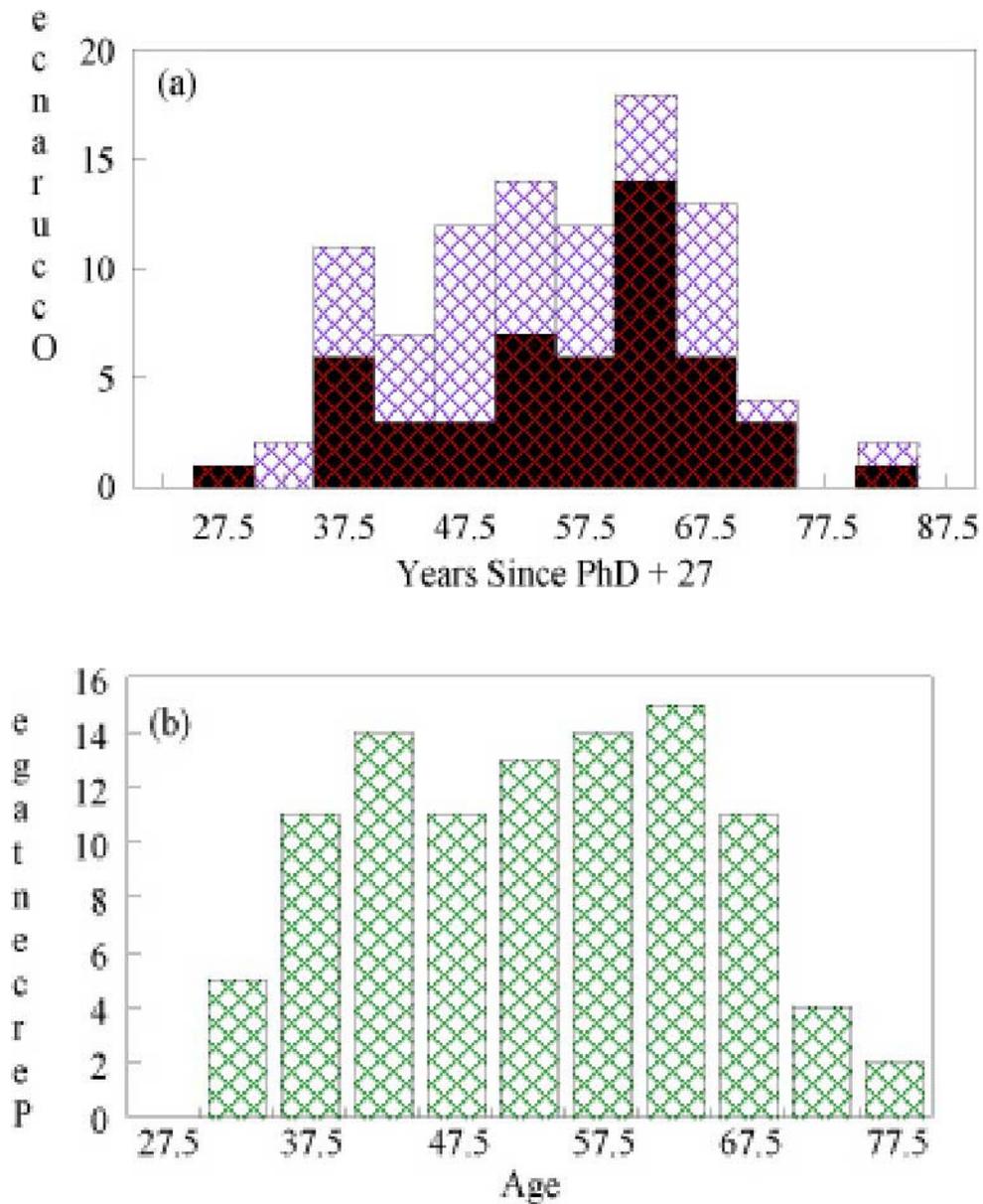


Figure 4.4. (a) The age distribution of fusion science faculty at 23 institutions with active plasma and fusion science programs. Data from six major centers of plasma physics (MIT, University of Maryland, University of Wisconsin at Madison, University of Texas, University of California, San Diego, and University of California, Los Angeles) are shown in red. (b) The age distribution of all physics faculty in U.S. colleges and universities. Courtesy of (a) University Fusion Association report, 2003, and (b) the American Institute of Physics

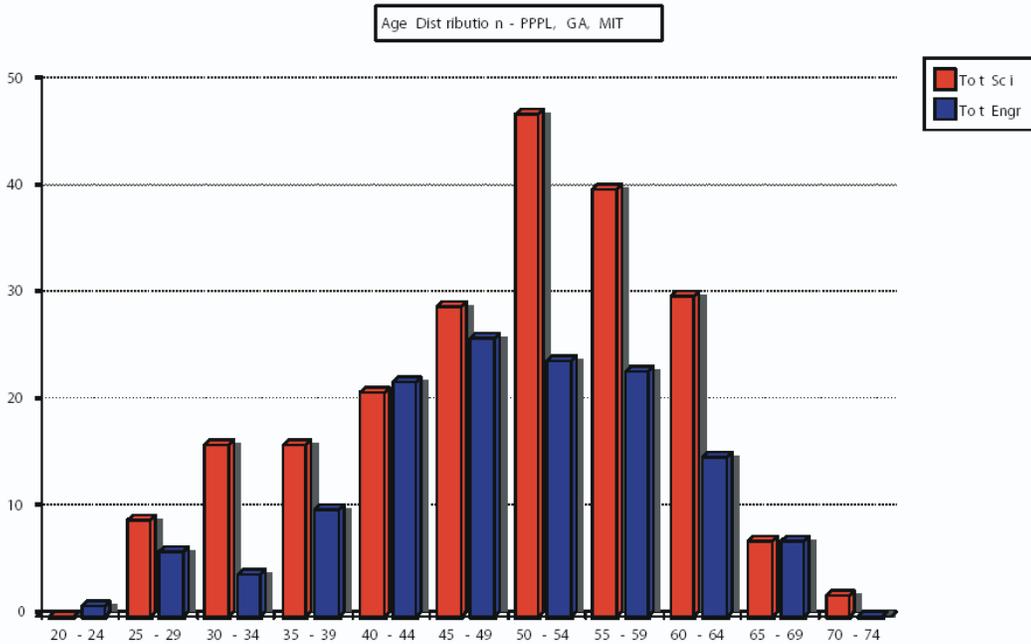


Figure 4.5. Age distribution of the scientific and engineering staff at the nation’s three largest fusion facilities, the Princeton Plasma Physics Laboratory, General Atomics, and MIT. This population comprises roughly one-half of the professional research staff supported by the fusion science program,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

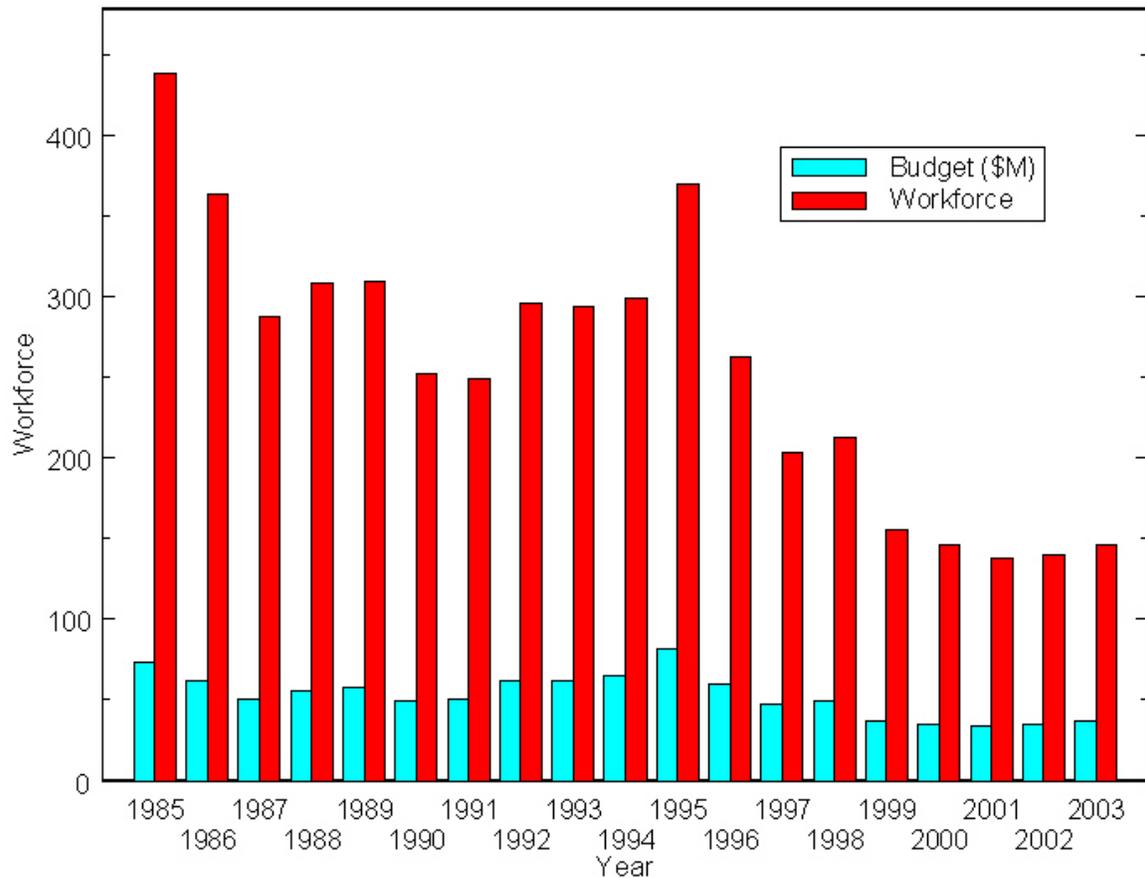


Figure 4.6 Trends in the technology workforce and budget since 1985. The trend shows that the fusion-technology workforce has sharply declined since the early 1990's, coincident with the de-emphasis of technology when the U.S. left the ITER project. Not only is this population aging, there is a concern that it may fall below the staff needed to optimize participation in a burning plasma experiment and gain maximum benefit from participation. Courtesy of X.

Appendices

A. CHARGE TO THE 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

BPAC 1st Meeting September 17-18, 2002 – Washington DC

Tuesday September 17th, 2002

Closed Session

8:00 am Committee Business

Open Session

1:30 pm Welcome and Introductions Ahearne / Fonck
1:45 pm OFES Perspective Anne Davies, OFES-DOE
2:30 pm OSTP Perspective Patrick Looney, OSTP
3:15 pm BREAK
3:30 pm DOE Perspectives Raymond Orbach, DOE
4:15 pm Open discussion Ahearne / Fonck
5:00 pm ADJOURN

Wednesday September 18th, 2002

Closed Session

8:00 am Committee Business

Open Session

9:00 am Committee resumes Ahearne / Fonck
9:05 am ITER presentation Karl Lackner, EFDA
10:05 am FIRE presentation Dale Meade, PPPL
11:05 am BREAK
11:30 am Snowmass Outcomes Jerry Navratil, Columbia University
Ned Sauthoff, PPPL

12:30 pm LUNCH
1:30 pm Report on FESAC action Stewart Prager, U Wisconsin
2:30 pm The "science first" approach Bruno Coppi, MIT
3:30 pm BREAK
3:45 pm Open discussion Ahearne / Fonck
4:45 pm ADJOURN
Closed Session
5:00 pm Committee Business
6:30 pm Meeting adjourns

BPAC 2nd Meeting November 17-18 2002 – Washington D.C.

Monday November 18th, 2002

Closed Session

8:30 am Committee Business

Open Session

9:00 am Fusion Power: I Think We're Lost Robert Hirsch

9:45 am	Q&A on DOE OFES program ITER Q&A session	Anne Davies, DOE Ned Sauthoff, PPPL
11:00 am	OSTP perspective	John Marburger, OSTP
11:30 am	BREAK	
11:40 am	ITER Q&A session (contd)	Ned Sauthoff, PPPL
12:10 pm	LUNCH	
1:15 pm	Comments by telephone	Marshall Rosenbluth, UCSD
Closed Session		
1:45 pm	Committee Business	
5:30 pm	ADJOURN	

Tuesday November 19th, 2002

Closed Session

8:00 am	Committee Business	
1:00 pm	ADJOURN	

**BPAC 3rd Meeting
January 17-18 2003 – La Jolla CA**

Friday January 17th, 2003

Closed Session

12:45 pm	Committee Business	
----------	--------------------	--

Open Session

2:30 pm	Remarks by phone	Anne Davies
2:45 pm	Additional elements of FESAC plan	Stewart Prager, U. of Wisconsin
3:30 pm	Break	
3:45 pm	Fusion power	Steve Dean, Fusion Power Assoc.
4:30 pm	Goldston FESAC report (Q&A)	Rob Goldston, PPPL
5:45 pm	ADJOURN	

Saturday January 18th, 2003

Closed Session

8:15 am	Committee Business	
---------	--------------------	--

Open Session

9:00 am	Review of U.S. Programs and Process	Mike Mauel, Columbia University
10:00 am	Break	
10:30 am	Future of tokamak facilities with a Burning Plasma Experiment	Ron Stambaugh, General Atomics
11:30 am	Multimachine strategy	Jerry Navratil, Columbia University
12:30 pm	Lunch	
<i>Closed Session</i>		
1:15 pm	Committee Business	
5:30 pm	ADJOURN	

Sunday January 19th, 2003

Closed Session

8:30 am Committee Business

12:00 pm ADJOURN

**BPAC 4th Meeting
May 5-6, 2003 – Washington D.C.**

Monday May 5th 2003

Closed Session

8:30 am Committee Business

Open Session

11:00 am DOE/OFES Program Plan

Anne Davies, OFES-DOE

11:45 am OSTP Perspective

J. Patrick Looney, OSTP

12:00 pm Lunch

Closed Session

1:00 pm Committee Business

5:30 pm ADJOURN

Tuesday May 6th 2003

Closed Session

8:00 am Committee Business

12:00 pm Lunch

1:00pm Committee Business

5:00pm Adjourn

C. PROPOSED BURNING PLASMA EXPERIMENTS

As detailed in the FESAC report, “A Burning Plasma Program Strategy to Advance Fusion Energy,” and discussed in much detail in the Snowmass reports, three burning plasma experiments have been proposed—ITER, FIRE and IGNITOR. These three experiments range from a reactor-scale device using superconducting magnets, to a compact, high-field copper-magnet device. 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.

The 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 the technology that will be required for a fusion power plant. A cut-away figure of the device is shown in figure 1.1 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 included one major redesign that reduced the anticipated cost by a factor of two 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 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 DT 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 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 3000 sec), high-fusion-power operation, the second phase of the experiment will

concentrate on 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 deuterium-tritium (DT) 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. There is expected to be significant erosion of the divertor due to repetitive oscillations of the plasma edge (ELMS). The projected tritium retention in re-deposited carbon has the potential to increase the machine downtime as a result 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 the confidence in the performance projections for ITER (as well as any other burning plasma experiment). This should also be a key element of the ongoing R&D program.

FIRE is a U.S. design study, in the advanced, pre-conceptual phase. Preliminary estimates indicate a cost of approximately \$1.3B 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, 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, to 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 is 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 deuterium-tritium 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 a technically sound design, FIRE, as presently proposed, 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 U.S. as much as participation in ITER while pursuing a more limited scientific mission and offering less in the development of new fusion technology. As such, the FIRE design should 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 MHD control, long-pulses and detailed profile measurements. Both FIRE and ITER have significant advanced tokamak 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 where long pulses and high neutron fluence is required. FIRE can explore advanced tokamak regimes with strong plasma shaping and active MHD control which 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.

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 deuterium-tritium 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, whether the required peaked pressure profiles can be realized, and the structural integrity of the vessel.

Table C.1: Parameters for burning plasmas in ITER (*ref. ITER web site*)

<u>Quantity</u>	<u>Value</u>
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

D. COMMUNITY RECOMMENDATIONS

The fusion community has been involved in many assessments of the best path for fusion science on the road to developing fusion as an energy source. Most recently this has involved the a 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 on *A Burning Plasma Program Strategy to Advance Fusion Energy* (September 2002), and most recently a FESAC report on *A Plan for the Development of Fusion Energy* (March 2003). The most prescient elements and recommendations of these efforts are presented in this section as summaries prepared by the committee with excerpts from each report 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 Dr. Jeffrey Freidberg (MIT) produced a report⁵⁵ with five recommendations. The panel concluded that “NOW is the time for the U.S. Fusion Energy 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.” The report suggested that the U.S. Fusion Energy Sciences Program should establish what they called “a proactive U.S. plan on burning plasma experiments” and to that end 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.” The panel also suggested that 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 Fall 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.” The panel suggested a course of action they felt would enable the presentation of an optimal burning plasma experimental plan to the nation no later than July 2004.

Snowmass Workshop

⁵⁵ DOE Fusion Energy Sciences Advisory Panel, *Review of Burning Plasma Physics*, 2001. (DOE/SC-0041).

Following the FESAC plan a Fusion Summer Study was organized in Snowmass, Colorado from July 8-19, 2002. The 2002 Fusion Summer 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 summary report⁵⁶ 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:

- 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.”

Here, only the elements of the workshop dealing with MFE are considered. At the end of the two 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.⁵⁷”

⁵⁶ R. Bangerter, G. Navratil, N. Sauthoff, *2002 Fusion Summer Study Report*, 2003.

⁵⁷ “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.”

(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)]:

- 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”

Prager Report

Following the Friedberg report’s strategy in February 2002, DOE Office of Science 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 (University of Wisconsin), met in Austin on August 6 – 8 2002 and its strategy recommendation⁵⁸ was adopted by FESAC on September 5. The panel based its recommendations on the Snowmass assessment with the aim of presenting a strategy to enable the U.S. to “proceed with this crucial next step in fusion energy science.” The report says that

“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 burning plasma program, providing the necessary knowledge base and scientific work force.”

The panel made two primary findings:

⁵⁸ DOE Fusion Energy Sciences Advisory Committee, *Report of the FESAC Panel on a Burning Plasma Program Strategy to Advance Fusion Energy*, 2002.

- “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.”

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 U.S.] 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.

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.”

Goldston Report

With the completion of the FESAC part of the Freidburg report’s plan of action, and with the continuing work of this NRC panel, DOE decided to charge a new FESAC panel to develop a plan for the deployment of a fusion demonstration power plant within 35 years, leading to commercial application of fusion energy by mid-century. The plan was developed by a committee under the leadership of Robert Goldston (PPPL) and dealt with development paths for both MFE and IFE, although we focus on the MFE aspects of the report here.

The Goldston report⁵⁹, adopted by FESAC on March 5, 2003, goes well beyond the DOE plan for a magnetic fusion burning plasma experiment envisioned in BPAC’s charge, including the consideration of inertial fusion energy. As such many aspects of the plan are not relevant to the charge before BPAC. Nevertheless, aspects of the MFE development plan as laid out in the Goldston panel report are relevant to this committee’s work.

The Goldston report says that key elements of its plan are:

- 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”.
- 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.”

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

Present – 2009

⁵⁹ DOE Fusion Energy Sciences Advisory Committee, *A Plan for the Development of Fusion Energy*, 2003.

- (1) “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.”
- (2) “Test fusion technologies in non-fusion facilities in preparation for early testing in ITER, including first blanket modules, and to support configuration optimization.”

2009 – 2019

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

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

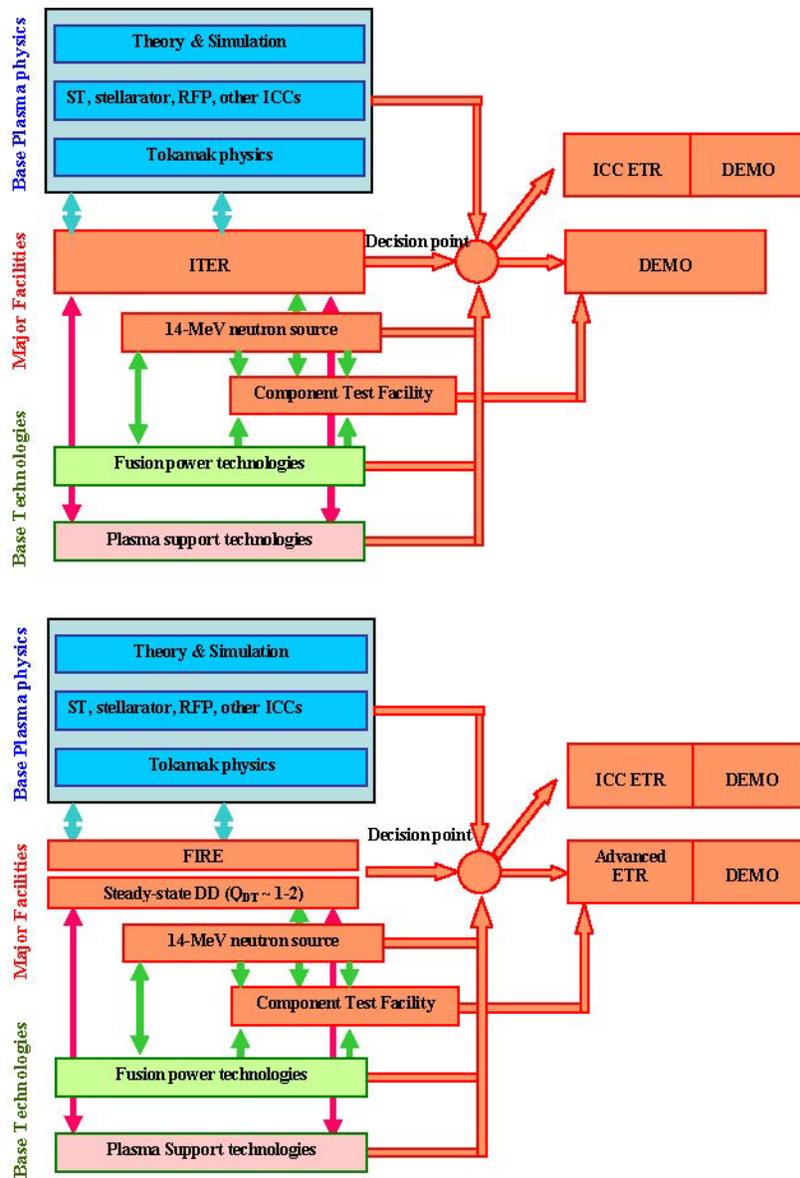


Figure D.1 Development Paths developed by Snowmass 2002 Fusion Summer Study workshop.

E. 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.

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

Overview

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

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

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

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

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

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

ITER Negotiations

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

Relation to Existing Fusion Energy Science Program

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

³ National Academy of Sciences, National Academy of Engineering, Institute of Medicine (SEM), Committee on Science Engineering and Public Policy (COSEPUP), *Science, Technology, and the Federal Government: National Goals for a New Era*, National Academies Press, Washington D.C., 1993.

⁴ Panel on Fusion Energy Research, President’s Committee of Advisors on Science and Technology, Office of Science and Technology Policy, Executive Office of the President, *The U.S. Program of Fusion Energy Research and Development*, Washington, D.C., July 1995, available online at <<http://www.ostp.gov/PCAST/fusionenergypub.html>>.

⁵ Snowmass 2002 Fusion Summer Study, Executive Summary, available online at <<http://web.gat.com/snowmass/exec-summary.pdf>>.

⁶ Fusion Energy Science Advisory Committee (FESAC) Panel Report, *A Burning Plasma Program Strategy to Advance Fusion Energy*, September 2002, available online at <http://www.ofes.fusion.doe.gov/More_HTML/FESAC/Austinfinal.pdf>.

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

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

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

Moving to Reenter Negotiations for ITER Participation

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

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

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

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

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

Scientific and Technological Value and Interest

Introduction

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

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

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

Scientific Importance

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

confinement, and they may therefore be expected to show new phenomena and changes in previously studied behavior.

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

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

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

Technological Importance

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

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

The behavior and integrity of materials in a fusion system are of great importance to the long-term viability of fusion energy. The high flux of energetic neutrons poses a serious materials problem that

will require substantial testing, some of which may be done on a burning plasma experiment and the rest of which may require a separate materials test facility. This will be discussed further in the final report.

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

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

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

Scientific and Technical Readiness to Pursue a Burning Plasma Experiment

Overview

This section summarizes the present state of scientific and technical readiness to undertake a burning plasma experiment. It relies on the results of the recent major burning plasma studies—FESAC 1997 ITER physics basis review,⁷ ITER final design report,⁸ and the Snowmass studies of 1999⁹ 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 tokamaks¹⁰) can be successfully fit using appropriate nondimensional discharge scaling parameters. This technique

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://www.foe.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).

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

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

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

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

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

Within this stable operating regime, there is another class of instabilities, called neoclassical tearing modes, that can degrade plasma performance. These instabilities depend strongly on the dissipation and transport properties of the plasma, and the theory for them is still in development. While this stability boundary cannot yet be predicted with precision, an important recent development is the discovery of a method to stabilize the plasma using localized, microwave driven currents. This stabilization technique is understood theoretically. The planned addition of microwave-based current-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 review¹¹ and the Snowmass studies of 1999⁹ and 2002⁵, 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.*

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://www.wofe.er.doe.gov/more_html/FESAC/ITER.Report.pdf

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

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

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

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

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

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

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

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

Conclusion

The committee agrees with the conclusions of the recent studies—namely, that the scientific and technical bases for proceeding with a burning plasma experiment have been established. Recent

theoretical and experimental progress in understanding and controlling tokamak plasmas and progress in developing burning-plasma-relevant technology provide added confidence that a burning plasma experiment can be carried out.

Summary

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

Sincerely,



John Ahearne
BPAC Co-Chair



Raymond Fonck
BPAC Co-Chair

F. FUSION REACTOR CONCEPTS

The Tokamak Configuration

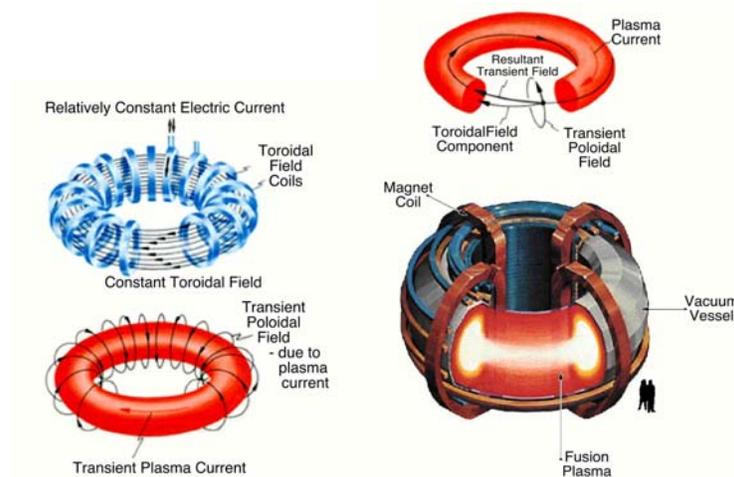


Figure F.1 This schematic shows the components of the tokamak confinement configuration, one of the more advanced plasma confinement concepts. It uses a strong toroidal field created by external field coils (top) to stabilize the plasma while using a poloidal field created by a toroidal plasma current to confine the particles. The final configuration includes a large vacuum vessel to isolate the hot plasma from the surrounding environment (bottom). Courtesy of General Atomics and Princeton Plasma Physics Laboratory

Extensions of the Tokamak – Spherical Torus and Spheromak

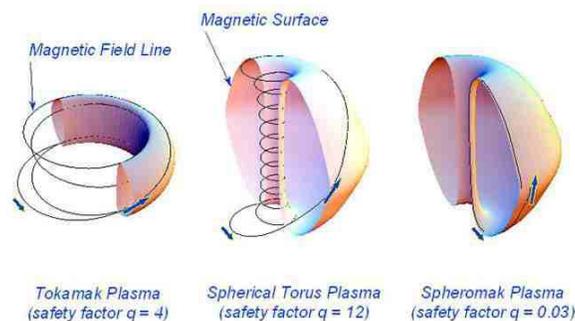


Figure F.2 Examples of the magnetic topologies of several related toroidal configurations with increasing curvature and varying stability characteristics. The tokamak (left) uses a strong external toroidal field to provide robust stability against pressure- and current-driven instabilities. The spherical torus uses a weak toroidal field in a compact configuration to allow access to higher β values than 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

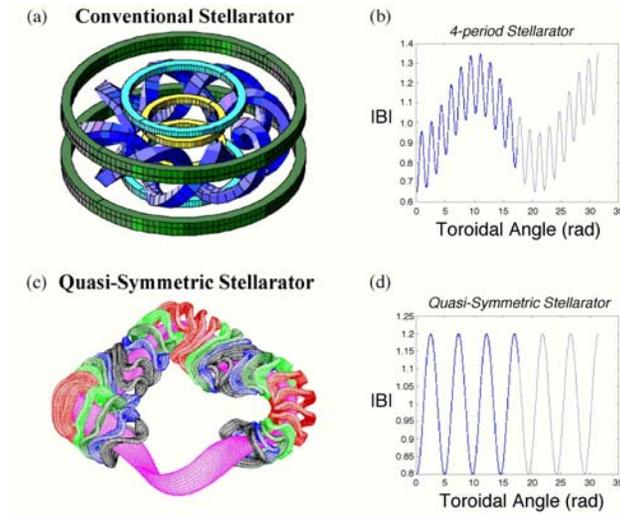


Figure F.3 The stellarator concept uses complex three-dimensional coil and magnetic flux surfaces to create a quasi-symmetric configuration in which the magnetic field appears to be only two-dimensional in the frame of reference of a moving particle in the plasma. The conventional stellarator (a) has 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 - Madison

The Reverse Field Pinch

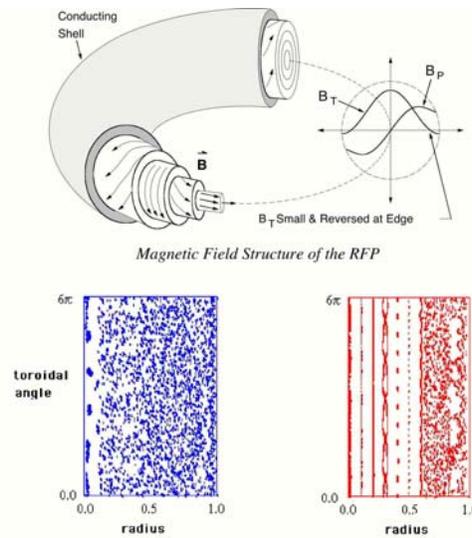


Figure F.4 A magnetic confinement concept such as the reversed-field pinch (top) is a relatively self-organizing configuration that is subject to turbulent magnetic field structures. The magnetic topology includes a reversal of the toroidal field inside the plasma owing to plasma currents. Under normal 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). Courtesy of S.C. Prager, University of Wisconsin – Madison.

G. COMMITTEE MEMBER BIOGRAPHIES

John 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 chairman 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 serves as chair of the NRC's Board on Radioactive Waste Management. In addition, Dr. Ahearne has been active in several National Research Council 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, and the 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. He received his Ph.D. in Physics from the University of Wisconsin-Madison in 1978. He was at Princeton University Plasma Physics Laboratory from 1978 through 1989, where he was Deputy Head of the PBX-M Tokamak project and head of the spectroscopy group on the TFTR experimental team. He joined the Department of Nuclear Engineering and Engineering Physics at Wisconsin in 1989. He presently heads the Pegasus Toroidal Experiment and directs collaborative experiments on the DIII-D National Fusion Facility. He is a Fellow of the American Physical Society, and served as President of the University Fusion Association for 1999-2000. He is a member of several Program Advisory Committees for large fusion science experiments, and served on the FESAC subpanel for U.S. participation in ITER. He also served as a member on the NRC Fusion Science Assessment Committee. He presently is chair of the Organizing Committee for the APS 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 principle investigator on grants from the Office of Fusion Energy Sciences of the Department of Energy.

John Bahcall is a Professor at the Institute for Advanced Study at Princeton University. He graduated from Harvard with a PhD in Physics in 1961. Following his Ph.D. he had the following appointments: Indiana University, Research Fellow in Physics, 1960-1962, CalTech, Res. Fellow, Asst. Prof., Assoc. Prof. of Physics: 1962-1970, Institute for Advanced Study, Member 1968-1969 (term II), 1969-1970; Professor Natural Sciences 1971-1997; and Richard Black Professor Natural Sciences 1997-date. In addition Dr. Bahcall has held the following positions: Hubble Telescope Working Group, At-Large Member, Interdisciplinary Scientist, 1973-1992; American Astronomical Society,

Councilor, President 1978-1981, 1990-1992; NAS, Chair, Section on Astronomy, 1980-1983; NRC, Chair Astronomy and Astrophysics Survey Committee, 1989-1991; NRC, Chair 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 Dr. Bahcall has received are Warner Prize American Astronomical Society, 1970; Sloan Foundation Fellow, 1968-1971; membership of, 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, United States 1998; Russell Prize, American Astronomical Society; Benjamin Franklin Medal in Physics, Gold Medal Royal Astronomical Society; and Dan David Prize all in 2003. Dr. Bahcall's research interest 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 Baym has been a faculty member of the University of Illinois at Urbana-Champaign since 1963. He obtained his PhD 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 a long and distinguished research career in the theory of many-body system, 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 ultrarelativistic 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 Science (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 at the Department of Mechanical Engineering and Physics at Yale University. He received his Bachelor's in Chemical Engineering from CUNY and his Ph.D. from NYU. He was a research scientist at the Westinghouse Research Laboratories (1950-54), a Senior Research Scientist at the Princeton University Plasma Physics Laboratory (1954-64), 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 the 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 on the Fusion Energy Science Advisory Committee of the Department of Energy, on the Plasma Physics Committee of the NRC, and on the Board of Physics and Astronomy of the NRC.

Stephen Cowley graduated with a Ph.D. from the Department of Astrophysical Sciences at Princeton University in 1985. Following his graduation Dr. Cowley served as a lecturer at Corpus Christi College at Oxford University, a senior scientific officer at the

U.K. Atomic Energy Authority (Culham Laboratory) before returning to the U.S. to work at the Plasma Physics Laboratory at Princeton University and eventually taking up a position as Professor at 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 ITER physics review panel. He has served as a member of the organizing committee for the annual Sherwood Fusion Theory meeting and he acted as chair of the NRC's Plasma Science Committee from 1999 -- 2001. Dr. Cowley was also a member of the NRC's Physics Survey Overview Committee that produced the overview volume for the Physics in A New Era decadal physics survey. He is currently serving on the committee reviewing 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 Frieman is an Emeritus Member of the Board of Directors of SAIC, Research Professor at the Institute of Geophysics and Planetary Physics and is Director Emeritus of the Scripps Institution of Oceanography. He previously served as Vice Chancellor for Marine Sciences at the University of California, 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. He graduated in 1951 with a Ph.D from Polytechnic Institute of Brooklyn. He has served as chairman of the NRC Board on Sustainable Development and as chairman of 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 DPP of the APS.

Walter Gekelman is a professor of physics at the University of California at Los Angeles (UCLA) and 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 include the auroral ionosphere, the magnetosphere, the solar wind, the solar corona, and the interstellar medium. Other topics he has studied are magnetic field-line reconnection, linear and non-linear plasma waves including a recent series 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, education outreach

and nominating committees. He has won numerous UCLA excellence in teaching awards and was an APS-DPP distinguished lecturer.

Joseph Hezir is the Co-founder and Managing Partner of the EOP Group, Inc a consulting company that specializes in regulatory strategy development and problem solving, and identifying newly created government business opportunities formed from mergers, acquisitions, joint ventures and new markets. Mr. Hezir served for eighteen 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 development of technology forecasts before returning to OMB in 1983 as Chief of the Non-Nuclear Energy Branch and from 1986 to 1992 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, the National Science Foundation, the Tennessee Valley Authority, the Nuclear Regulatory Commission, and the Smithsonian Institution. Currently a member of the Critical Technologies Sub-Council of the Competitiveness Policy Council, Mr. Hezir also was 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 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. Mr. Hezir then completed graduate studies at Carnegie-Mellon in Urban and Public Affairs, specializing in environmental and energy policy. He also served as an advisor to Allegheny County, PA 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 Nevins received his Ph.D. in Physics from UC Berkeley in 1979, and did post doctoral research at the Princeton Plasma Physics Laboratory before moving to the Lawrence Livermore National Laboratory where he is a senior Scientist in the Fusion Energy Program. His research interests include microturbulence, both kinetic and MHD instabilities in mirror machines (the major experiment at LLNL in the early 1980's), and the absorption of intense microwave pulses by plasmas (a key issue for the Microwave Tokamak Experiment at LLNL in the late 1980's). Dr. Nevins spent most of 1988-1992 working on the ITER CDA design. He is currently the PI for the Plasma Microturbulence Project—a collaboration between LLNL, PPPL, U of MD, U of CO, UCLA, and GA 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 Fusion Energy Sciences Advisory Committee (FESAC) panels—including the 1995 FESAC panel, which recommended a science-based Fusion Energy program, the 2001 and 2002

FESAC panels which recommended that the U.S. program proceed with a Burning Plasma experiment.

Ronald Parker is professor of nuclear engineering and electrical engineering and computer science at Massachusetts Institute of Technology. He obtained the Ph. D. in electrical engineering at MIT in 1967. Honors include ERDA Distinguished Associate Award, Fellow, American Physical Society, APS Award for Excellence in Plasma Physics, and membership in the National Academy of Engineering. From 1992 - 1998, he was on leave from MIT to serve as ITER Deputy Director and head of the ITER Co-Center in Garching, where he was responsible for the design of the ITER in-vessel systems. After resuming academic duties at MIT in 1998, he 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 RF and bootstrap current drive. In addition, he has recently initiated a new look at fusion-fission hybrids, including 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 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 Chairman of the National Synchrotron Light Source and Co-Chairman of the newly formed Center for Accelerator Physics. In 1989 Prof. 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, of the Scientific Policy Committee of the Stanford Linear Accelerator Center, of the Cornell University Nuclear Physics Laboratory, and of the Free Electron Laser Center at Vanderbilt University. Professor Pellegrini is a Fellow of the American Physical Society. In 1996 he was elected Chair of the Division of Physics of Beams of the American Physical Society. He has also been the Chairman of the Panel on Advanced Accelerators of the International Committee for Future Accelerators. He is presently a member of the National Research Council Committee on Plasma Physics. Professor Pellegrini was awarded the International Free-electron Laser Prize in 2000, and the Wilson Prize of the American Physical Society in 2001. He is presently the Chair of the UCLA Department of Physics and Astronomy.

Burton Richter is the Paul Pigott Professor of Physical Sciences at Stanford University and is the Director Emeritus of the Stanford Linear Accelerator. He received his Ph.D. from MIT in 1956. He has produced over 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 the 1974 Loeb Lecturer, Harvard University, 1975 DeShalit Lecturer, Weizmann Institute, and 1976 E.O. Lawrence Medal (DOE). He is a fellow of the American Academy of Arts and Sciences, APS and AAAS. 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 Surko is a Professor of Physics at the University of California, San Diego. He received his Ph.D. from the University of California, Berkeley in 1968. He was a member of the technical staff and department head at AT&T Bell Laboratories, Murray Hill, N.J. (1970 - 88). 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 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 served as a member of FESAC and he served on the FESAC Burning Plasma Panel.

Michael Ulrickson received his PhD in Nuclear Physics at Rutgers University in 1975. Dr. Ulrickson began investigating the properties of graphites for use as plasma facing components (PFCs) at Princeton Plasma Physics Laboratory (PPPL) in 1975. Introduction of graphite components into the Princeton Large Torus resulted in peaked plasma temperature profiles and improved energy confinement time. Continued research on graphite and carbon fiber composite materials lead to the selection of carbon based materials for the plasma facing components for the Tokamak Fusion Test Reactor (TFTR). This work eventually led to the selection of carbon fiber composite as the preferred plasma facing material. He was a member of the Deuterium-Tritium Materials Physics Group that successfully predicted the tritium retention during DT experiments on TFTR. In 1988, he was given 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. plasma facing component research supporting the International Thermonuclear Experimental Reactor (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 U.S. and directed the design of PFCs for the FIRE burning plasma device.

Michael Zarnstorff is the head of the Physics Team for the National Compact Stellarator Experiment (NCSX). He received his Ph.D. in Physics in 1984 from the University of Wisconsin - 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. His 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-Shear-Stabilization Effect and vertical Charge-Exchange-Recombination diagnostics. He has collaborated on other experiments in the UK, Japan, and Germany, as well as in the U.S. 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 by the Laboratory. 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 understanding how 3D shaping of magnetic fields and equilibria affects plasma MHD stability and transport.

Ellen Zweibel is Professor of Astronomy and Physics at The University of Wisconsin, Madison, where she moved in January 2003. Previously she was Professor of Astrophysics and Fellow of JILA at U. Colorado, Boulder. She chaired her department from 1989-1992, 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 & 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 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. degree from Princeton in Astrophysical Sciences in 1977.

GLOSSARY

Advanced Tokamak (AT): A tokamak that would operate continuously with the current driven by a combination of non-inductive 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 waves: A fundamental plasma phenomenon, which is primarily magnetohydrodynamic in character: oscillation of the magnetic field and, in some cases, plasma pressure. In tokamaks, these waves are typically strongly damped (i.e. 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

ARIES: A comprehensive tokamak fusion power plant study 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 present 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. Several more advanced configurations have been studied as well, ARIES-RS used a reversed-shear tokamak while ARIES-AT studied an advanced tokamak.

Auxiliary Heating: Heating additional to Ohmic heating. Used to heat tokamaks to temperatures at which Ohmic heating is small. Usually uses neutral beams or radio-frequency waves.

Beta: $\beta = p/(B^2/2\mu_0)$. The ratio of plasma gas pressure (p) to magnetic field pressure ($B^2/2\mu_0$) in a tokamak. p is the gas pressure in Pascals (Newton/meter²), B is the magnetic field strength in Tesla, and $\mu_0 = 4\pi \times 10^{-7}$ Henry/meter.

Beta limit: Maximum beta attainable, usually due to a deterioration in the confinement.

Blanket: The physical system surrounding the hot plasma that 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: Theory predicted in 1970 that a toroidal electric current will flow in a tokamak which is fuelled 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 JET and TFTR; it now plays a role in 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 for a long enough time at high enough density and temperature in order to be economically feasible.

Confinement, Magnetic: 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 and this confines their motion to the local vicinity of the magnetic field. A properly shaped magnetic field prevents particles from escaping the confining field. One example of a magnetic confinement device is a tokamak.

Confinement time: Time taken 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 (RF) power generators.

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

Deuteron: Nucleus of a deuterium atom.

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

Disruption, disruptive instability: A complex phenomenon involving MHD 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/ helium ash to a target chamber.

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 ($\approx 40 - 50$ keV). Accordingly, it will be the preferred fuel in fusion power plants. The reaction is: $D + T \rightarrow He4 + n + \text{energy}$

Edge-Localized Modes (ELM): An instability which occurs in short periodic bursts during the H-mode in divertor tokamaks. It causes transient heat and particle loss into the divertor which can be damaging.

ELM: See Edge-Localized Modes

FESAC: The Department of Energy's Fusion Energy Science Advisory Committee.

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 Mega Amperes. 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 has happened, the alpha-particles have no further use: they constitute helium ash, whose removal and replacement by deuterium-tritium fuel is 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"), ELMs, and about a 100% increase in energy confinement time compared to the normal L-regime.

Ion Cyclotron heating: Additional heating method using RF waves at frequencies (about 20-50 MHz) matching the frequency at which ions gyrate around the magnetic field lines.

ITER: The International Thermonuclear Experimental Reactor will be burning plasma experiment based on the tokamak concept—the leading magnetic confinement fusion concept named after a Russian word for toroidally (or donut) shaped magnetic field. ITER is expected to be larger than existing tokamaks with a major radius of 5 to 8 meters 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 and the United States.

JET: See Joint European Torus

Joint European Torus: the largest tokamak in the world, is sited at Culham in the United Kingdom.

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

L-mode: As opposed to the H-regime. The "normal" Low confinement regime of additionally heated tokamak operation.

Magneto Hydrodynamics: 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.

MHD: See Magneto Hydrodynamics.

MFE: Magnetic Fusion Energy

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

Minor Radius: The radius of the small cross section (small circle) of a torus.

Mode: Another word for wave or oscillation in a plasma.

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

Neoclassical Tearing Modes: 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. This is the neo-classical tearing mode.

Neutral-beam Heating: An energetic beam of neutral particles. Typically produced by accelerating a charged particles, or ions, which are subsequently neutralized in an electron exchange process. In magnetic fusion neutral beams use isotopes of hydrogen and are primarily used to heat the plasma.

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

Pedestal, Temperature: In H-mode there is a region of steep temperature gradient at the plasma edge. The temperature at the top of this steep gradient region is the temperature pedestal.

Plasma: A state of matter characterized by un-bound negative electrons and positive ions which may conduct electrical current. Plasma is often called the fourth state of matter, along with the other states of matter: solids, liquids and gases. It is estimated that more than 99% 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 vary in particle density from about $10^6/\text{m}^3$ (solar wind) to $10^{30}/\text{m}^3$ (core of 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: 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 (c.f. stellarator); this is in contrast to the larger toroidal field, which is generated externally.

Reconnection, Magnetic: refers to 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.

Reverse-field pinches: 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} Hertz.

Scaling laws: Empirical or theoretical expressions for how various plasma phenomena (e.g. confinement, power threshold, etc.) 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 where 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; see torsatron, heliotron, helias. In general, stellarators have not been as successful as tokamaks though a considerable level of research continues, notably in Germany, Spain, USA, Russia and Japan.

Tearing modes: A class of resistive MHD instability which has been predicted theoretically in tokamaks.

TFTR: See the Tokamak Fusion Test Reactor

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

Tokamak Fusion Test Reactor: was the largest U.S. device located at the Princeton Plasma Physics Laboratory, and performed a major campaign using deuterium and tritium fuel between 1993 and 1997. TFTR 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. 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: Shape of a simple donut. 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 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 non-existent in nature. Tritium can be produced by bombarding lithium with a neutron and inducing a fission reaction. $\text{Li6} + \text{n} \rightarrow \text{T} + \text{He4} + 4.8 \text{ MeV}$ or $\text{Li7} + \text{n} \rightarrow \text{T} + \text{He4} + \text{n} - 2.5 \text{ MeV}$

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.