FINAL REPORT OF THE COMMITTEE ON A STRATEGIC PLAN FOR U.S. BURNING PLASMA RESEARCH

Committee on a Strategic Plan for U.S. Burning Plasma Research

Board of Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of
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Preface

Following decades of scientific research, including the successful production of 11 MW fusion power in the Tokamak Fusion Test Reactor experiment in the United States and 16 MW in the Joint European Tokamak in the United Kingdom, an international agreement to build and operate a burning plasma experiment was formalized in Paris with the signing of the *Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project* in November 2006. The signatories of the ITER agreement—the United States, China, the European Union, India, Japan, the Republic of Korea, and the Russian Federation—are building the world's largest international scientific research facility, called ITER. When construction is complete, scientists will share in the operation and results of ITER; create, study, and control burning plasma; and demonstrate fusion power production at least 10 times greater than the power needed to sustain the plasma. This will be a scientific and technical achievement and a critical step toward producing and delivering electricity from fusion energy.

Since the international establishment of the ITER project, an international design review was completed in 2008; ITER construction began in 2010; and ITER became the first-of-its-kind, licensed, basic nuclear fusion facility in 2012. However, by 2013, ITER's construction schedule had slipped, and ITER's costs had increased significantly, leading to questions of whether the United States should continue its commitment to participate in ITER. These concerns resulted in a directive from Congress, appearing in the Consolidated Appropriations Act, 2016, that the Secretary Energy report to Congress on U.S. participation in the ITER project, including budget projections, project schedule, project management, and foreign policy implementations.

The Secretary's report was delivered to Congress in May 2016 and recommended that the United States remain a partner in the ITER project through fiscal year (FY) 2018. The report acknowledged the significant construction progress made at ITER and the substantial improvements in ITER project management. The Secretary's report also stated that ITER appears to be technically achievable and is the best candidate today to demonstrate sustained burning plasma. Although fusion power holds the possibility of providing abundant energy, the Secretary's report noted that significant technical and management risks remain before the project will be completed and recommended "the U.S. re-evaluate its participation in the ITER project to assess if it remains in our best interests to continue our participation." In addition to outlining various oversight and management reviews to ensure continued improvement in ITER project performance, the Secretary's report requested advice from the National Academies of Sciences, Engineering, and Medicine,[1] as follows:

> To perform a study of how to best advance the fusion energy sciences in the U.S., given the developments in the field since the last Academy studies in 2004, the specific international investments in fusion science and technology, and the priorities for the next ten years developed by the community and the Office of Fusion Energy Sciences (FES) that were recently reported to Congress. This study will address the

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in a historical context identifying programs prior to July 1.

> scientific justification and needs for strengthening the foundations for realizing fusion energy given a potential choice of U.S. participation or not in the ITER project, and will develop future scenarios in either case.

In response to this request, the Committee on a Strategic Plan for U.S. Burning Plasma Research was established. The committee's statement of task is given in Appendix A. The statement of task requested the preparation of two reports.

The first, an interim report, was released on December 21, 2017, and is reprinted in Appendix I. It presented the committee's assessment of the current status of U.S. fusion research and of the importance of burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

For this report, the second and final report, the committee was asked to provide guidance on a strategic plan for a national program of burning plasma science and technology research given the U.S. strategic interest in realizing economical fusion energy in the long term. Strategic guidance was to be provided in two separate scenarios in which the United States is, or is not, a member in ITER. The committee was also asked to consider the health of the domestic fusion research sectors (universities, national laboratories, and industry), participation by U.S. scientists in international activities, and what role international collaboration should play over the next 20 years.

This report represents the consensus of the committee after seven meetings (see Appendix B for the meeting agendas). The first two meetings informed preparation of the interim report. The final five meetings were devoted to the scientific and technical bases for a variety of strategic elements under consideration within the United States and to improve understanding the strategic plans for Europe, China, Japan, and the Republic of Korea. The committee visited the two major fusion research facilities within the United States; toured the superconducting magnet facility at Poway, California, where the large ITER central solenoid magnets are being manufactured; and learned first-hand of the European fusion energy strategy during a visit to the ITER construction site. Additionally, the committee heard about the fusion energy strategies of the two largest privately funded fusion ventures within the United States from Bob Mumgaard, chief executive officer of Commonwealth Fusion Systems (CFS) and Michl Binderbauer, president and chief technology officer of TAE Technologies.

The committee is very grateful for the input from two weeklong community workshops on Strategic Directions for U.S. Magnetic Fusion Research, hosted by the University of Wisconsin, Madison, in July 2017 and by the University of Texas, Austin, in December 2017. These workshops were highly successful, involved hundreds of researchers across the country, and provided the committee with several dozen technical documents on the scientific and engineering challenges and opportunities associated with advancing magnetic confinement fusion as an energy source. The committee appreciates the tremendous effort of the U.S. fusion energy research community in providing expert input. We are especially grateful for the leadership of the workshop co-chairs, David Maurer, Jon Menard, Hutch Neilson, and Mickey Wade.

Several important findings became apparent during the committee's deliberations, and they are detailed in its two reports. First, the programmatic focus on preparing for ITER experiments has resulted in tremendous progress in the understanding and prediction of a burning plasma. By way of well-instrumented experiments, advanced theory, and state-of-the-art computer simulation, the international community of fusion scientists is much more ready to carry out burning plasma experiments in ITER today than when the Burning Plasma Assessment Committee released its report[2] in 2004. Confidence that ITER will achieve its scientific mission has improved. Second, the pace of advancing technology has been rapid, and numerous technology breakthroughs, some of which developed independently from fusion, appear to offer a viable pathway to lower the cost and shorten the time required to demonstrate fusion power. These technologies were described in a report of the subcommittee of the U.S. Department

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[2] National Research Council, 2004, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C.

of Energy's (DOE's) FESAC on Transformative Enabling Capabilities (TEC) Toward Fusion Energy, released in February 2018. The FESAC report identified technologies, especially including high magnetic field and critical temperature superconductors and advanced materials and manufacturing, with the potential to transform fusion power systems to become more economically attractive for commercialization. The application of these new technologies to fusion energy, when combined with the significant progress in understanding the complex processes within a magnetized burning plasma, are the underpinnings for the committee's strategic guidance for a cost-attractive pathway to fusion power.

During the committee's study, we received encouragement and support from many individuals to whom we are indebted; these include Jim Van Dam of DOE's Office of Fusion Energy Sciences; Nat Fisch, member of the National Academies Board on Physics and Astronomy; Bill Dorland, chair of the National Academies Plasma Science Committee; and James Lancaster, director of the Board on Physics and Astronomy. The committee is also grateful to the following physicists and engineers who made important technical contributions to the preparation of the interim and final reports: Mohamed Abdou, Hans-Henrich Altfeld, Amitava Bhattacharjee, Bernard Bigot, Richard Buttery, Tony Donné, Gianfranco Federici, Phil Ferguson, Stefan Gerhardt, Chuck Greenfield, Martin Greenwald, Sibylle Guenter, Richard Hawryluk, Dave Hill, Amanda Hubbard, Yong-Seok Hwang, Thomas Klinger, Mike Jaworski, Sam Lazerson, Gyung-Su Lee, Jiangang Li, Tim Luce, David Maurer, Jon Menard, Yuichi Ogawa, Stewart Prager, Soren Prestemon, Juergen Rapp, Ned Sauthoff, Oliver Schmitz, Ed Synakowski, Tony Taylor, Mickey Wade, Dennis Whyte, and Mike Zarnstorff.

On a more personal note, we would like to express our sincere appreciation to all members of the committee for their dedicated efforts for more than a year in the preparation of both reports. We are especially grateful to Stanley Kaye, Philip Snyder, Brian Wirth, and Amy Wendt who took leadership in the drafting of the chapters of the final report. We would also like to express our appreciation to the staff of the National Academies, particularly to David Lang and Christopher Jones, for their advice and highly professional guidance in the final preparation of the interim and final reports. We are truly indebted to them for their insights and extraordinary contributions throughout the committee's study process.

Michael E. Mauel and Melvyn Shochet, *Co-Chairs*
Committee on a Strategic Plan for U.S. Burning Plasma Research

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

Richard Buttery, General Atomics,
James D. Callen, NAE,[1] University of Wisconsin, Madison,
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Joseph Hezir, EOP Group, Inc.,
Robert Iotti, ARC Nuclear,
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Jonathan Menard, Princeton University,
David Petti, Idaho National Laboratory,
Anne White, Massachusetts Institute of Technology, and
Steven J. Zinkle, NAE, University of Tennessee, Knoxville.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Martha P. Haynes, NAS, Cornell University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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[1] Member, National Academy of Engineering.
[2] Member, National Academy of Sciences.

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Executive Summary

Fusion energy offers the prospect of virtually unlimited energy, and the United States and many nations around the world have made enormous progress toward achieving fusion energy. Many of the complex physical processes of magnetically confined plasma are now understood, and the first construction phase of the international ITER fusion reactor is more than half complete. With the initial operation of ITER scheduled to begin within a decade and with the expectation, 10 years later, that controlled fusion will be demonstrated, now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take steps towards the development of fusion electricity for the nation's future energy needs.

This report of the Committee on a Strategic Plan for U.S. Burning Plasma Research describes a strategic plan for fusion research to guide implementation of the committee's two main recommendations:

- First, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.
- Second, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.

ITER is a burning plasma experiment and the critical next step in the development of fusion energy. It is a large and ambitious project that integrates multiple advanced technologies and combines the scientific and engineering expertise, industrial capacity, and financial resources of many nations. As a partner, the United States receives full benefit from the technology developed for ITER while providing only a fraction of the financial resources. Methods to control the plasma and extract the electricity-producing heat will be tested and developed. U.S. industry is building major systems for ITER and thereby gaining expertise in fusion engineering science and building industrial capabilities.

Although the United States provides only part of the cost of ITER, if the United States is to profit from its share of the ITER investment, the nation's strategic plan for fusion should combine its ITER experience with the additional science and engineering research needed to realize reliable and economical fusion electricity. Without this additional research, the United States risks being overtaken as other nations advance the science and technology required to deliver a new and important source of energy.

Recent advances motivate a new national research program leading to the construction of a compact fusion pilot plant. Significant progress in predicting and creating the high-pressure plasma required for such a reactor has been made. Opportunities to develop technologies for fusion, such as high-temperature superconducting magnets and advanced materials, now make a compact device possible. A focus on a compact device will accelerate the fusion development path, making it affordable and attractive for industrial participation. Finally, by starting now, a national research program toward a compact pilot plant and critical science and technology research can be ready in time to use the knowledge learned from ITER operation to demonstrate electricity production by mid-century.

The committee envisions a U.S. pilot plant producing power similar to that expected in ITER but in a device much smaller in size and cost and employing design improvements that would allow net electricity production. This compact burning plasma fusion pilot plant would be a pre-commercial research facility. In addition to the production of fusion electricity, it would ultimately be capable of uninterrupted operation for weeks and produce tritium, the heavy isotope of hydrogen in fusion fuel. As a pilot plant, its purpose will be learning, but the knowledge obtained would be sufficient to design the first commercial fusion power systems.

A new national focus on developing a compact pilot plant in the long term will help set priorities for the near and mid-term fusion program. Research needs to show how to increase the fusion power density beyond that obtainable in ITER. Uninterrupted operation should be demonstrated while researchers learn how to handle reliably the high levels of escaping heat from the plasma. New program elements should begin immediately to develop the materials and technologies needed to extract the heat and recirculate tritium and, also, to promote the industrial development of very-high-field superconducting magnets for fusion. Finally, technology innovations should be encouraged and developed to simplify maintenance and lower construction cost.

The committee recognizes that there are risks involved in developing a compact fusion pilot plant. Resolving these risks will necessitate the design and operation of new facilities. One of the greatest risks is the control of a continuous high-pressure compact plasma, which will require a design and construction of new intermediate-scale research facility in the United States, or a significant upgrade to an existing facility, to establish its feasibility. Another significant risk is the qualification of the materials and components that surround the plasma and are exposed to fusion irradiation. The committee's proposed strategic plan also includes other recommendations aimed at improving and reducing the cost of fusion as a source of electricity through the development of promising innovations in burning plasma science and fusion engineering science.

The committee expects that the implementation of its recommendations, including both continued participation in ITER and the start of a national research program for a compact pilot plant, will require additional funding, rising to nearly $200 million beyond the recently enacted annual funding levels. This funding would need be sustained for several decades. Although the funding remains level, the research portfolio evolves over time, and existing research facilities are phased out as new ones are implemented.

The committee was also tasked to recommend strategic guidance if the United States decides to withdraw from the ITER project. This withdrawal would significantly disrupt the national research effort, isolate U.S. researchers from the international effort, and eliminate the benefit of sharing the cost of producing a burning plasma at the power plant scale. Nevertheless, if the United States decides to withdraw from the ITER project, the committee recommends the United States continue research toward the construction of a compact fusion pilot plant. However, without ITER participation, U.S. progress will necessitate a significantly larger commitment of resources for a longer time. Without ITER, the United States would need to design, license, and construct an alternative means to gain experience creating and controlling an energy-producing burning plasma. The scale of research facilities within the United States would become larger, more ambitious, and more expensive. As a result, producing net electricity from fusion in the United States would be delayed.

1

Introduction

Fusion energy offers the prospect of abundant, virtually unlimited energy, and the United States and many nations around the world have made enormous progress toward achieving fusion energy. Many of the complex physical processes of magnetically confined plasma are now understood, and the first phase of ITER construction is more than half complete. With the initial operation of ITER scheduled to begin within a decade and with the expectation, 10 years later, that controlled fusion will be demonstrated, now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take steps towards develop fusion electricity for the nation's future energy needs.

This report of the Committee on a Strategic Plan for U.S. Burning Plasma Research presents guidance on a strategic plan for a U.S. research program of burning plasma science and technology directed toward realizing economical fusion energy. It builds on the committee's interim report,[1] which provided assessments of the importance of burning plasma research to the development of fusion energy and of the current status of burning plasma research in the United States. Although significant scientific and engineering challenges are described, the committee concluded that the knowledge developed through decades of fusion research is now sufficiently advanced to propose a path to demonstrate fusion generated electricity within the next several decades. This strategy requires continued partnership in the international effort and strengthened research within the United States. Many technical details of the proposed strategy need further development and input from the U.S. fusion energy science community. Nevertheless, based on the advanced state of understanding the science of magnetic confinement, new developments in superconducting magnets and advanced manufacturing methods, the considerable expert input received, and the committee's expertise, the committee concludes a research pathway that includes study of a burning plasma and leads to the construction of a compact fusion pilot plant at the lowest possible capital cost is technically sound and strategically warranted. This strategic guidance can be developed for two scenarios: if the United States continues as a partner in the ITER project, or if it does not. However, if the United States decides to withdraw from the ITER project, the United States would need to design, license, and construct an alternative means to gain experience creating and controlling an energy-producing burning plasma. Without ITER participation, the scale of research facilities within the United States would become larger, and the achievement of electricity production from fusion in the United States would be delayed.

The following introduction is organized into four sections: (1) a brief background, (2) a summary of the committee's approach to its task, (3) a summary of the committee's assessments within the interim report, and (4) an outline and guide to the overall structure of this final report, including the committee's findings and recommendations.

BACKGROUND

Fusion is the process that powers the sun and thereby enables life on Earth to exist. It occurs when hydrogen-like particles at extremely high temperature fuse to make a heavier element, like helium. In this process energy is released, eventually appearing as heat. Fusion electrical power plants would produce no carbon-based pollutants, have minimal long-lived radioactive waste, and benefit from an almost limitless fuel supply. The most successful concept and the subject of this report is a fusion power plant consisting of a steadily burning plasma confined by a very strong magnetic force field within a donut-shaped vessel. In order for more power to be released by fusion reactions than needed to maintain the temperature of the burning plasma, above 100 million degrees Kelvin, the burning plasma must have sufficiently large size and strong magnetic field so that the energy released by fusion reactions provides most of the power needed to keep the plasma hot. Although significant fusion power has been generated for short periods in the laboratory, a burning plasma, which is heated predominately by fusion reactions, has never been created. This requires construction of a burning plasma experiment such as the International Thermonuclear Experimental Reactor (ITER). While ITER is a science and technology experiment, a future fusion power system will be built with additional advanced technologies that will allow uninterrupted operation, guide escaping plasma heat from the burning plasma out of the vessel in a controlled way, produce the fusion fuel in blankets that surround the burning plasma, and convert the radiating energy from fusion to electricity in the same way as in existing power plants.

The United States became an ITER partner in 2007 after signing a binding international agreement[2] with China, the European Union (EU), India, Japan, the Republic of Korea (ROK) and Russia to build and operate a burning plasma experiment at the scale of a power plant. ITER is a large and ambitious project that integrates multiple advanced technologies and combines the scientific and engineering expertise, industrial capacity, and financial resources of several nations. As a burning plasma experiment, ITER is a critical step along the path to advance the science and technology of a fusion power source. The first phase of ITER construction is now more than half complete. The ITER Organization (IO) plans for initial operation of the facility by the end of 2025.

The decision to construct ITER was a milestone in fusion energy research. Fusion scientists had successfully built, operated, and studied a series of experiments with strong magnetic fields and increasing size. Using these experiments, they learned how to confine and control high-pressure plasma at temperatures exceeding 100 million degrees. In the largest experiments,[3,4] significant fusion power was produced for seconds, and some of the processes expected in a burning plasma were studied at the temperatures and pressures required for fusion energy. In 2004, the NAS Burning Plasma Assessment Committee[5] concluded that the global fusion community was technically and scientifically ready to undertake a burning plasma experiment like ITER. Since that report, research has further increased confidence that ITER will achieve its scientific mission and allow scientific studies of burning plasma at the power plant scale.[6]

When fully completed, ITER will be capable of producing energy comparable to the output of a power plant and will allow study of many of the interconnected science and technology issues needed to develop magnetic fusion energy as a practical source of power. Scientists will use ITER to test methods to control plasma stability, plasma interactions with first wall materials, plasma confinement, and fusion power output. Theoretical predictions of energetic particles produced by fusion reactions and methods to sustain a burning plasma for pulses longer than five minutes will be explored and validated. Equally important are gains in fusion engineering science and industrial capability that are resulting from assembly and operation of large superconducting magnets, safe management and recovery of tritium, remote handling of in-vessel components, progress in evaluating fusion blanket options, and experience with large-scale project management.

While experiments with ITER will lead to major gains along the path to fusion energy, additional science and engineering challenges need to be addressed before fusion power can be produced in a reliable, economical, and socially acceptable way. In a commercial system, the fusion power density would need to increase and uninterrupted operation should be available for more than a year. Energetic neutrons impinging on the surrounding wall and the escaping heat from the plasma need to be handled reliably. The lithium-containing blankets that surround the plasma need to produce safely unprecedented quantities of tritium, the heavy isotope of hydrogen. Technology innovations should be encouraged and developed to simplify maintenance and lower construction cost. Any strategic plan for fusion power requires both study of a burning plasma experiment and research beyond what will be done in a burning plasma experiment to improve and fully enable commercial fusion power.

National strategic plans leading to the demonstration of fusion power have been adopted by our international partners. Similar strategies have been discussed within the United States in the past. However, for more than a decade, the United States has not had a long-term strategic plan for fusion energy. This Final Report provides guidance for such a plan for the United States.

The U.S. DOE/FES presented its current vision for fusion research to Congress in 2015.[7] The overall mission is to "expand the fundamental understanding of matter at very high temperatures and densities and build the scientific foundation needed to develop a fusion energy source." United States fusion research emphasizes two frontiers in burning plasma science: "the physics of self-heated burning plasma state" using ITER as the vehicle for gaining access to this state, and the "great scientific challenge for fusion is to develop materials that can tolerate the extreme conditions created by burning plasma in a fusion reactor." The majority of the U.S. DOE/FES program budget contributes to developing the predictive understanding needed for ITER operations and providing solutions to high-priority ITER research needs. A smaller element, called "Discovery Plasma Science," represents about 15% of the annual fusion budget and supports research that advances fundamental understanding of ionized matter, or plasma, in support of non-fusion applications. Nevertheless, these fundamental plasma studies inform both non-fusion and fusion applications. As applied to fusion energy science, they develop and test underlying concepts that underpin fusion plasma theory and simulation efforts and assist in the development of validated simulation capabilities to predict fusion plasma performance and behavior. The U.S. DOE Office of Science has not presented a plan for research and technology programs needed to progress beyond ITER to a source of fusion power.

The United States research focus on ITER has resulted in significant burning plasma research advances and improved confidence in ITER burning plasma performance. Examples of new progress include improved understanding and modeling of plasma confinement, demonstration of long-pulse magnetic confinement, achievement of high plasma pressure comparable to values expected in ITER, improved understanding of plasma exhaust processes, and successful demonstration of several techniques to control transients. However, other fusion energy science and technology efforts within the United States that did not directly support ITER have been reduced or eliminated. Fusion technology efforts were reduced and domestic experimental facilities were closed limiting scientific and engineering opportunities within the United States and weakening the potential to build expertise in fusion science and technology and guide needed research alongside ITER.

The absence of a long-term research strategy for the United States is particularly evident when compared to the plans of our international partners. The NRC Committee to Review the DOE Plan for U.S. Fusion Community Participation in the ITER Program[8] observed "international partners in ITER are explicitly organized toward developing fusion energy and a Demonstration Power Plant (DEMO). This focus gives them a clear goal for their development of fusion power." The 2008 NRC report further recommended that "existing gaps in planning for a demonstration power plant" should be addressed in further development of U.S. DOE planning. EUROfusion (the consortium agreement of research organizations and universities from 26 European Union countries plus Switzerland, Ukraine, and formerly the European Fusion Development Agreement) is guided by a roadmap to supply fusion electricity to the grid by the 2050s.[9] Similar national roadmaps leading to the demonstration of fusion power guide research in China[10] and Japan.[11] The committee's Interim Report also noted the importance of strategic planning to guide national research and innovation programs, to engage industrial partners, and to set national priorities and concluded, "if the United States seeks to continue its pursuit for abundant fusion power, the development of a national strategic plan for fusion energy that spans several decades is necessary."

Since joining the ITER project, the U.S. fusion community and its advisory committee, the Fusion Energy Sciences Advisory Committee (FESAC),[12] have responded to requests from the U.S. DOE Office of Science to identify the issues arising in a path to fusion demonstration, with ITER as a central part of that effort, and to prioritize the additional interconnected scientific and technical questions to be answered. Appendix C presents a summary of these strategic planning activities conducted from 2001 to 2018. Fourteen FESAC reports and four community workshops, sponsored by the U.S. DOE Office of Science are summarized. These reports recommended programs of research to address all of the scientific challenges of fusion energy including fusion engineering, materials science, and plasma physics.

One difficulty for recent U.S. fusion energy strategic planning has been the substantial growth in ITER construction costs and schedule slippage. In response to cost and schedule concerns, the ITER

Council charged an independent team, chaired by William Madia, former director of Oak Ridge National Laboratory and Stanford University vice president for the Stanford Linear Accelerator Center, to determine the causes for ITER's cost increases and schedule delays and to make management recommendations. These recommendations resulted in significant management improvements by the ITER Council and the appointment of Bernard Bigot as the new ITER director in March 2015. The ITER Council approved a new Updated Long-Term Schedule to first plasma in June 2016, and the U.S. DOE was able to approve the project execution plan for U.S. contributions to ITER in January 2017.[13] A measure of the success of ITER's management reforms is the fact that two years after the creation of the updated long-term schedule, the project remains on schedule for first plasma in 2025 and, since January 2016, has achieved all 33 scheduled project milestones.[14]

The preceding paragraphs and the additional background within Appendix C present the context for the committee's study and its strategic guidance for burning plasma science and technology directed toward realizing fusion energy. On the one hand, the U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence in the success of ITER and our ability to learn a great deal from its operation. On the other hand, the interconnected science and technology needed for fusion are not fully developed. Many challenging questions still need to be answered through scientific discovery and dedicated interdisciplinary study in plasma physics, materials science, fusion nuclear technology, and engineering science. New research facilities and initiatives need to be designed and constructed to carry out the additional research needed to realize fusion electricity. Long-term goals should be set so that priority choices can be made. The U.S. research portfolio will need to evolve in time as existing research facilities are phased out as new ones are implemented.

To be compelling, a new strategy should incorporate technical innovations and insights that enable a lower cost development path than was proposed in past strategic plans. Also, a compelling plan should take into consideration ITER's updated management and schedule, and allow cost-effective study of both a burning plasma experiment and the research and technology programs needed beyond what is done in a burning plasma experiment. After adopting a nationally endorsed strategic plan for delivery of fusion energy, the United States can better set research priorities, promote innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and attract the talented scientists and engineers who will drive research toward commercially viable fusion reactor designs. Describing the elements of this compelling plan is the purpose of this final report.

COMMITTEE APPROACH

In the course of developing its strategic guidance, the committee considered past strategic plans proposed for the United States, the strategic plans of other nations, recent developments, and the input from community experts. The committee first worked to understand whether the science and technology of magnetic fusion has advanced sufficiently to justify adopting a national plan toward realizing fusion power for the United States and how a national strategic plan developed today is different from past strategic plans. This required understanding the progress and challenges for magnetic fusion energy, the status and schedule of the ITER project, the potential contributions from other international research activities, and the opportunities for progress within the Unites States. The committee then set out to define the steps required to realize economical fusion energy for the United States in the long term.

As required by the committee's Statement of Task (Appendix A), the focus of this Final Report is the advancement of magnetic confinement fusion energy given the U.S. strategic interest in realizing economical fusion energy in the long-term. As a consequence, the committee did not comment on questions of program balance within the U.S. DOE Office of Science between non-fusion plasma science and research in support of magnetic fusion energy. As this Final Report is being written, the committee notes the start of a new *Decadal Assessment of Plasma Science* by the National Academies[15] that will provide valuable information and guidance on issues that pertain to plasma science to the federal agencies and policy makers in both Congress and the Administration.

The past strategic plans[16] proposed for the United States development of fusion energy consisted of four elements: (1) magnetic confinement systems, (2) understanding and controlling a burning plasma, (3) developing materials systems that can withstand the energetic fusion neutrons and the escaping plasma heat impinging on the inner wall, and (4) fusion nuclear technology consisting of a fusion "blanket" that both converts the energy released from fusion reactions to electricity and also creates from lithium the heavy isotope of hydrogen, tritium, which should be safely recovered and used as fusion fuel. Figure 1.1 illustrates one strategic pathway as presented in the 2004 NRC Report of the Burning Plasma Assessment Committee.[17] Research from all four elements need to be completed to inform a future "decision point" leading to the demonstration of fusion power and construction of a DEMO facility. A DEMO would produce electricity, operate routinely and eliminate all technical barriers to the commercialization of fusion power. Prior to a DEMO decision, both non-nuclear and nuclear fusion research occurs. Non-nuclear research in magnetic confinement systems aims to understand and predict how plasma pressure can be confined by configuring the magnetic pressure imposed from strong superconducting magnets. Non-nuclear technology research includes enabling systems that heat and control a burning plasma, the engineering sciences for strong superconducting magnets, and the techniques to handle the escaping heat from the plasma.

The remaining activities in Figure 1.1 are fusion nuclear facilities: a burning plasma experiment, like ITER, a source of 14-MeV neutrons that would advance scientific understanding of radiation effects phenomena in the materials that will surround a fusion plasma, and a fusion component test facility that will test and develop the lithium-containing fusion "blankets" necessary to create the fusion fuel, tritium, and convert energetic neutron energy into useful heat. Because they are fusion nuclear facilities, they operate with nuclear operating licenses, like the first-of-a-kind basic nuclear fusion license given to ITER by French Order of 7 February 2012.[18]

All strategic plans for fusion energy contain the elements depicted in Figure 1.1. But, today, the sequence of activities can be quite different from Figure 1.1 for several reasons. First, the international fusion research community is now much stronger, having made good progress toward fusion. Our international partners have demonstrated world-record achievements in long-pulse plasma confinement and have successfully constructed and operated leading research facilities with superconducting magnets. These experiments have provided increased confidence in the prospect for sustained, uninterrupted fusion power. Second, while past plans required the design, siting, and construction of a burning plasma experiment, today's planning can build upon the continued progress of the ITER project and the significant investment of the international community already underway. With the schedule of the ITER Project newly baselined and on-track, strategic plans can expect burning plasma studies using ITER will inform the next steps in the development of fusion energy. Third, fusion strategic planning is also different today because of advances in the theoretical understanding of toroidal magnetic confinement and plasma control that provide integrated solutions to optimize the burning plasma regime. Finally, remarkable new technologies, largely developed outside the fusion research effort, promise to reduce the size and cost of future facilities that will demonstrate the production of fusion electricity. Unlike the pathway shown in Figure 1.1, a large DEMO device no longer appears to be the best long-term goal for the United States program. Instead, science and technology innovations and the growing interest and potential for private-sector ventures to advance fusion energy concepts and technologies suggest that smaller, more compact facilities would better attract industrial participation, shorten the time and lower the cost of the development path to commercial fusion energy.

Permission Pending

FIGURE 1.1 Development path for realizing fusion power as a practical energy source, developed by the Snowmass 2002 Fusion Summer Study Workshop. Basic research in plasma physics and technologies support major fusion faculties leading to decision point for a DEMO device. SOURCE: National Research Council. 2004. *Burning Plasma: Bringing a Star to Earth*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10816, p. 152.

The committee reviewed past strategic plans, the advancement in magnetic fusion confinement science, and the recent breakthroughs in fusion-relevant technologies with the goal to develop a new lower-cost roadmap for the United States. The committee asked several questions:

- Has the science and technology of magnetic fusion advanced sufficiently to justify adopting a national plan toward realizing economical fusion power for the United States?
- With the expected start of ITER experiments within the next decade, will U.S. researchers be ready to benefit from burning plasma experiments and begin the next steps, beyond ITER, toward the demonstration of fusion electricity?
- How can the U.S. program develop a unique research strategy that benefits from the large international effort and avoids the cost of duplicated effort?
- Can advances in modeling, prediction, and simulation be used to make wise facility investments and improve overall research effectiveness?
- Finally, can new technologies, like high magnetic field and high critical temperature superconductors, and new material designs and advanced fabrication, like additive manufacturing, lower the cost of fusion development and provide an affordable plan that builds upon the ITER research experience and is consistent with appropriate long-term funding scenarios leading to fusion electricity?

The committee answered these questions through deliberation and through detailed consideration of technical input from the fusion research community.

COMMUNITY AND EXPERT INPUT

In the course of developing its strategic guidance, the committee placed high value on community and expert input and the considerable scientific progress reported in scientific and technical journals.[19] In addition to the review of past studies on magnetic fusion energy strategy and research needs, the committee heard from representatives from the European Union, China, Japan, and the Republic of Korea (ROK) who addressed the committee and described near-term and long-term research plans. The committee conducted visits to the national fusion research facilities at General Atomics and the Princeton Plasma Physics Laboratory and walked through the ITER construction site located besides the Cadarache research center of the French Alternative Energies and Atomic Energy Commission (CEA). Over fifty technical white papers were received; more than two dozen technical lectures were presented to the committee during seven open meetings (Appendix B); and references to more than 300 technical and scientific papers were cited to illustrate the progress in fusion energy science research.

The committee also benefited from two independent strategic planning activities (Appendix E). The first was a series of community workshops, titled “U.S. Magnetic Fusion Research Strategic Directions.”[20] The goals of the workshops were to discuss, debate, and develop critical technical information required for the development of a strategic plan, including program mission and goals, and to present and discuss opportunities to achieve those goals through the pursuit of various scientific and technical programs. These workshops were highly successful and involved hundreds of researchers across the country. Workshop participants prepared detailed technical reports on nine strategic research program elements, descriptions of various strategic approaches to fusion research planning, and summaries of important working group topics such as the impact of ITER access to U.S. fusion scientists and the requirements for attractive fusion power systems. The second activity supporting magnetic fusion strategic planning was the work of the Subcommittee of the U.S. DOE FESAC on Transformative Enabling Capabilities (TEC) Toward Fusion Energy. FESAC released the subcommittee’s report in February 2018,[21] which identified “the most promising transformative enabling capabilities (TEC) for the U.S. to pursue that could promote efficient advance toward fusion energy, building on burning plasma science and technology.” The report identified several technologies (advanced computer algorithms, high magnetic field and high critical temperature superconductors, advanced materials and manufacturing, novel technologies for tritium fuel cycle control, and fast flowing liquid metals) each with “tremendous opportunity to accelerate fusion science and technology toward power production” and with the potential to transform fusion power systems to become more economically attractive for commercialization.

ASSESSMENTS FROM THE INTERIM REPORT

The Final Report builds on the committee’s seven assessments of the status and importance of U.S. burning plasma research to the development of fusion power presented in the Interim-Report.[22] These are:

> **Assessment 1:** Burning plasma research is essential to the development of magnetic fusion energy and contributes to advancement in plasma science, materials science, and the nation’s industrial capacity to deliver high-technology components.
>
> **Assessment 2:** The U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.
>
> **Assessment 3:** Construction and operation of a burning plasma experiment is a critical, but not sufficient, next step toward the realization of commercial fusion energy. In addition to a burning

plasma experiment, further research is needed to improve and fully enable the fusion power system.

Assessment 4: Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.

Assessment 5: Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.

Assessment 6: Any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary for such an inherently large project. A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.

Assessment 7: If the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy.

The first two assessments address the importance of burning plasma research to the development of fusion energy science and describe the achievements of the United States research program contributing to increased confidence in burning plasma studies to be conducted with the ITER device. The next three assessments describe programmatic shortfalls in the United States program that threaten the health of the field and hamper progress in necessary fusion technology research to improve and fully enable fusion power. The last two assessments from the Interim Report deserve emphasis because they directly relate to the committee's strategic guidance.

As explained in Assessment 6, as an ITER partner the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary to create and study burning plasma at the scale of a power plant, *i.e.* ITER. Because burning plasma research in support of ITER and in preparation for ITER experiments is a primary focus of the international and U.S. research programs, ITER is more than a construction project. ITER plays a central role in today's U.S. burning plasma research activities, and participation in the ITER project provides formal mechanisms for U.S. scientists to take leading roles in the international effort to develop fusion energy. Additionally, because the vast majority (approximately 80 percent) of U.S. ITER construction funding remains within the U.S. supply chain, participation in ITER has resulted in significant advances in U.S. domestic industrial capabilities and capacities that would not have happened without ITER participation.

A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma. The impact of a decision to withdraw from ITER would be disruptive. Because there is currently no mature burning plasma experiment as an alternative to ITER, the design, construction, and licensing of such an alternative to ITER would require significant development by the U.S. program, as well as a new approach to avoid isolation from the international fusion energy research effort.

The committee's study in preparation for the Final Report has reinforced its conclusion that continuation as a partner in the ITER project best serves the nation's strategic plan for fusion energy. For this reason, the primary guidance within this Final Report assumes continued U.S. participation in ITER and presents a strategy for the demonstration of fusion electricity that benefits from ITER operation and from new developments in technologies that will lower fusion's development costs. The committee did not find any reasonable or compelling strategy for fusion power development without ITER participation, and no such strategy was presented to the committee that could provide a technical basis for recommended guidance. What the committee does provide, nevertheless, is a generic plan if the United States decides to withdraw from ITER having similar goals but requiring a larger commitment of resources for longer periods of time.

As explained in Assessment 7, if the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy. This assessment reinforces the recommendations of the NRC Committee to Review the DOE Plan for U.S. Fusion Community Participation in the ITER Program and echoes the recommendations of Congressional leaders and the 2014 GAO Report.[23] After adopting such a plan, the United States can better set research priorities and attract the talented scientists and engineers who will drive research toward commercially viable fusion reactor designs. Indeed, now is the right time to expand the U.S. effort beyond the study of a burning plasma and include the accompanying research to fully enable fusion power. If the United States is to profit from its share of the ITER investment, a strategic research plan directed toward realizing fusion energy in the long term is necessary.

As a result of research progress and the potential for new technologies to improve the economic attractiveness of fusion power and lower the cost of fusion development, the committee's guidance presents a plan for the United States to benefit from its investment in burning plasma research and take steps towards the development of fusion electricity for the nation's future energy needs. Four elements important to the committee's guidance are:

- Continued progress toward the construction and operation of a burning plasma experiment leading to the study of burning plasma,
- Research beyond what is done in a burning plasma experiment to improve and fully enable commercial fusion power,
- Innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and
- A mission for fusion energy research that engages the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

Today, there is little doubt that fusion energy can be produced in the laboratory. The questions now being asked are different than before and cannot be answered by science alone. Whether fusion can be done in a reliable, economical, and socially acceptable way requires finding inventive solutions to challenges that intersect science, technology, and engineering and combining the talents of plasma scientists and skilled engineers. These remaining challenges are by no means trivial. Fusion research and development would need to be sustained for several more decades, and major new test facilities will need to be carefully designed and constructed. Needless to say, fusion research, like any grand undertaking, will be most successful when guided by a national strategic plan that sets priorities, supports decision-making, and establishes a long-term goal by which to measure progress.

STRUCTURE OF THE FINAL REPORT

The following five chapters describes the committee's guidance for a strategic plan leading to the production of electricity from a compact fusion pilot plant:

- Chapter 2 describes scientific and technical progress and how this progress has improved confidence that a burning plasma experiment, like ITER, will succeed. Chapter 2 provides three findings about this progress and further developments needed to progress beyond ITER toward fusion electricity.

- Chapter 3 describes the important burning plasma science to be learned from participation in ITER and how the United States can benefit from ITER participation and inform the design of a compact pilot plant. Chapter 3 concludes with three findings describing the scientific and technical benefits from ITER, the importance of ITER in the U.S. program, and how advancements in understanding magnetic confinement point to improvements beyond the ITER baseline and with two recommendations for how the U.S. DOE FES should conduct both the near-term and long-term ITER research. Chapter 3 also includes two findings describing research needs if the U.S. withdraws from the ITER project and states the committee's recommendation that the United States should not withdraw. However, even in the scenario without ITER participation, the U.S. DOE/FES should still initiate a plan leading toward the construction of a compact fusion pilot plant. In the scenario without ITER, an alternate means to study a burning plasma and to engage the international community would be required.
- Chapter 4 describes the interconnected science and technology research within the new national program. It describes research building upon ITER results and reaching the lowest possible capital cost for the compact pilot plant. Chapter 4 concludes with a detailed finding itemizing the technical and scientific support motivating a new national research program leading to the construction of a compact pilot plant. Chapter 4 also concludes with four recommendations to the U.S. Department of Energy in the start and planning of its new program of accompanying research and technology leading to the compact pilot plant. These include resolving five critical research needs, planning for the construction of new research facilities, and the adoption of a two-phase approach to its plans for the compact pilot plant so that scientific and technical risks can be addressed cost-effectively.
- Chapter 5 reviews the forgoing chapters and summarizes the committee's strategic guidance for U.S. burning plasma research. The committee's two main recommendations are elaborated. This chapter summarizes program elements, an approximate research timeline, a response to a decision to withdraw from ITER, and budget implications of the committee's guidance.
- Chapter 6 discusses organizational structure, program management, and other management goals to further strengthen United States fusion research with partnerships with related efforts within the U.S. Department of Energy, with industry, and with the international research community. Chapter 6 concludes with five findings and seven recommendations aimed to guide the implementation of an expanded U.S. DOE FES research program and strengthen community participation in the burning plasma science, materials science, fusion nuclear sciences, and engineering sciences needed to realize an economical pathway to fusion electricity for the nation.

The following chapters contain many technical details of the proposed strategy based on study and deliberation. However, the committee expects its guidance will need further technical development and further input from the U.S. fusion energy science community. Nevertheless, based on the advanced state of understanding the science of magnetic confinement, new developments in superconducting magnets and advanced manufacturing methods, the considerable expert input received by the committee, and the committee's expertise, the committee's Final Report provides a technically sound pathway that gains experience with a burning plasma at the scale of a power plant and that also starts a national plan for the accompanying research and technology leading to the construction of a compact pilot plant at the lowest possible capital cost and the production of electricity from fusion.

NOTES

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19. Appendices C, D, and E provide the agendas for committee meetings and site visits, bibliography of past studies consulted, and summary of input received from the fusion research community.
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2

Progress in Burning Plasma Science and Technology

This chapter describes progress in burning plasma science since the United States joined the ITER partnership by way of international agreement.[1] Since then, experiments using research facilities in the United States and in other nations have been highly productive. New ideas to control and sustain a burning plasma have been discovered, and theoretical and computational models developed in the United States have substantially improved the ability to control plasma stability, predict plasma confinement, and enhance fusion energy performance. Methods to control and mitigate transients and scenarios that will guide operation of ITER have been successfully tested. Confidence that ITER will succeed in achieving its scientific mission has substantially improved, and progress in burning plasma science and technology has motivated research beyond what will be achieved in ITER toward fusion electricity.

The following first describes progress in burning plasma science and technology that has resulted from the international effort to prepare for ITER operation. This progress combined with ITER construction progress (Figure 2.1) demonstrates a high-level of readiness to undertake burning plasma experiments and the expectation that the burning plasma regime can be accessed for detailed study. Next, this chapter discusses the scientific and technical readiness to undertake research beyond ITER and address the potential for economical fusion electricity. Finally, this chapter concludes with a summary of three findings about progress and the further developments needed to progress beyond ITER toward fusion electricity.

RESEARCH PROGRESS IN SUPPORT OF ITER

The 2004 NAS Burning Plasma Assessment concluded that the global fusion science community is both scientifically and technically ready for proceeding with a burning plasma experiment. Scientific readiness was determined from empirical confinement predictions, knowledge of operational limits set by plasma stability, methods to mitigate abnormal events like plasma current disruptions, the ability to maintain plasma purity, methods to measure and characterize a burning plasma, and techniques to control a burning plasma. Technical readiness was determined by successful prototyping of ITER components, evidence of adequate component lifetime in a nuclear environment, tests of plasma-facing components and materials, initial analysis of the safe control of tritium, demonstrations of remote maintenance systems, and demonstration of the required fueling, heating, and current drive control.

Since the 2004 assessment, the ITER design was reviewed and updated in 2008.[2] The updated ITER physics basis[3] reflected progress from major experiments around the world. Scientists from the United States and from other nations significantly advanced the basic understanding of the processes expected in burning plasma, tested scenarios that will be used to study burning plasma, and achieved significant progress toward construction of the ITER facility through international cooperation. Experiments conducted using research facilities in the United States have discovered new ideas to control a burning plasma that can be tested in ITER. New experiments built with superconducting magnets in China and the Republic of Korea have demonstrated long-pulse plasma with high confinement properties. United States researchers have used NSTX to test innovative divertor configurations and understand plasma rotation and kinetic effects on the stabilization of instabilities. Using the DIII-D national research facility, fusion scientists have discovered and tested techniques to control edge localized modes, test disruption mitigation schemes for use on ITER, and experimentally verified computational models to help predict ITER operation. Record plasma pressure was achieved in the Alcator C-Mod experiment at MIT. Experiments using Alcator C-Mod, and the JET and ASDEX-U devices in Europe demonstrated use of a metallic first-wall in preparation for similar experiments in ITER. Theoretical and computational models

FIGURE 2.1 Arial photograph of the ITER site. Construction began in 2010 after site preparatory work. By December 2017, more than half of ITER total construction work through first plasma was complete. On June 2018, ITER construction continues on track having achieved all 33 Council-approved project milestones scheduled since January 2016.

developed in the United States have substantially improved the ability to control plasma stability, predict plasma confinement, and enhance fusion energy performance.

The ITER Organization (IO) and a team of international scientists developed the ITER Research Plan (IRP) in 2013.[4] This plan was recently revised with the updated ITER schedule.[5] The IRP presents a program logic for a sequence of plasma operations with hydrogen, helium, deuterium, and ultimately deuterium-tritium mixtures for fusion power production. Through dedicated experiments, research, and study by the international community, all of the science and technical criteria that established the readiness for burning plasma experiments in 2004 have progressed greatly.

In the next sections, scientific readiness for ITER operation is presented, including these main areas of research: (1) plasma confinement predictions, (2) plasma stability and operational boundaries, (3) energetic particle physics, (4) mitigations of transients and abnormal, events, and (5) technical progress for ITER construction and technology.

Plasma Confinement Predictions

The understanding and optimization of plasma transport, and the ability to predict the plasma response to both collisional and turbulence-induced transport, have advanced considerably beyond the stage when only empirical scaling-laws were employed to predict the performance of ITER. Physics based optimization of confinement performance in both the core and edge of magnetically confined plasmas is one of the critical areas in present day burning plasma research.

A strength of the U.S. theory and simulation program is its close connection to experimental studies, which fosters the validation of the simulation tools and theory to existing observations. Examples include (1) multi-scale predictions of turbulent transport,[6,7] which have been subsequently observed in experiment,[8] (2) the impact of turbulence on neoclassical tearing modes (NTM),[9,10] and (3) the development of high-gain scenarios for ITER and other planned devices.[11] While extensive validation against experimental databases of reduced models is still required, examples of the success of this reduced model development is seen in Figure 2.2, which shows the comparison between reduced model predictions and experimental observations for the plasma core (Figure 2.2a) and plasma edge (Figure 2.2b). These two models have been coupled to produce the core-edge optimized scenarios for burning plasma studies.[12] The coupling of experiment and theory, along with expanded computational capabilities, have been determined through experimental observations of turbulence characteristics as well as through comprehensive, physics-based numerical simulations.

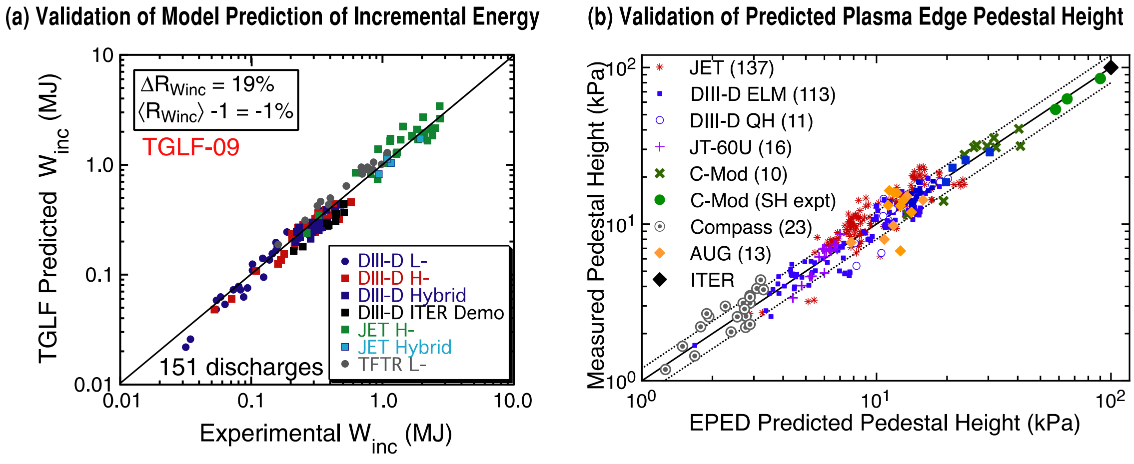

FIGURE 2.2 Validation of model predictions for plasma pressure and energy. (a) Comparison of reduced model prediction to experimental measurements of core plasma stored energy and (b) comparison of predicted and measured edge pedestal pressure. SOURCE: Kinsey et al., Nucl. Fusion 51:083001, 20111 (b) Snyder et al., Nucl. Fusion 51:103016, 2011.

An example of successful core-edge plasma optimization is to improve the performance of a burning plasma. This achievement was made possible by the recently developed capability to use physics-based core-edge coupled numerical simulations to predict plasma characteristics across the entire plasma. The predicted scenario was achieved through strong plasma shaping and by carefully controlling the trajectory of the plasma density to open access to a regime with stable, high density and pressure plasma edge.[13,14] This optimization has led to the achievement of record pedestal pressures that are within approximately 10% of the ITER target[15] and also led to equivalent fusion power gain, defined as Q, with D-T equivalent Q over 0.5 achieved on DIII-D.[16] Another optimization led to another world record for the average plasma pressure achieved for any fusion device, as indicated in Figure 2.3. While the ITER target goal of $Q = 10$ can be achieved with the expected performance in conventional operation, applying these optimization techniques to ITER plasmas can potentially enhance performance beyond the $Q = 10$ range.

Research has led to the understanding of zonal flows in plasma turbulence,[17] and the role of single and multi-spatial scale effects in driving transport.[14,18,19,20]**Error! Bookmark not defined.** Research has shed light on the structure and formation of the H-mode pedestal. [21,22,23] In plasma stability, an understanding of the effects of and plasma response to applied 3D magnetic perturbations,[24,25] as well as of the plasma behavior during disruptions[26] and disruption mitigation,[27] has been developed. Finally, comprehensive simulations[28] have been used to understand processes controlling the scrape-off layer heat flux width, and they project to a more optimistic scenario for heat flux width on ITER than previously thought.[29]

Plasma Stability and Operational Boundaries

Magnetohydrodynamic (MHD) instabilities in tokamaks are large-scale perturbations to the plasma that are driven by the plasma pressure and current, and which can lead to degradation of plasma performance through enhanced radial transport of plasma and energetic particles. If not controlled, a larger-scale instability may lead to abrupt terminations of the plasma, called “disruptions.” Operational boundaries are defined by those plasma parameters where these instabilities can be avoided or controlled. For the ITER baseline scenario for achieving $Q = 10$, pressure-driven kink and resistive wall instabilities[30] are avoided by operating below plasma pressure limits. However, the ITER baseline scenario is susceptible to neoclassical tearing modes (NTM) that are driven by plasma current density.[31,32] Significant progress toward meeting the challenge posed by tearing instabilities has occurred for the ITER baseline stability by way of better understanding of the roles of plasma rotation, plasma collisionality, and the use

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FIGURE 2.3 Maximum pressure obtained in 49,110 discharges spanning the lifetime of the C-Mod experiment (+), vs. $B\ I_P\ /\ a$, where the average plasma pressure is given by $\langle P \rangle$ (Pa) = 4000 β_N ($B\ I_p/a$). The world record pressure was obtained using high magnetic field (B = 5.7 T) and physics-based optimization. The ITER target parameters are indicated, as well as some noteworthy high-performance discharges from the TFTR, JET, and DIII-D experiments. See J.W. Hughes, et al 2018 Nucl. Fusion in press https://doi.org/10.1088/1741-4326/aabc8a.

of various control actuators, including cancelation of unwanted magnetic field errors[33] and localized plasma current drive[34] and optimized with advanced feedback and search algorithms.[35]

Active techniques include tailoring the plasma profiles with various heating and current drive schemes, as well as applying 3D magnetic field perturbations at the plasma edge.[36] Achieving high plasma β_N can also be aided by a judicious choice of plasma shaping and configuration. For instance, in the more "spherically shaped" NSTX plasmas, stable high-β_N discharges were produced routinely with the aid of stabilization techniques.[37] Stabilization studies in the mid-sized U.S. tokamaks DIII-D and NSTX-U, along with further development of techniques to stabilize and control the plasma, including development of physics-based models of MHD instability thresholds, are necessary to inform decisions on an optimized shape and configuration for producing steady-state plasmas in a fusion pilot plant. Steady-state operation with large self-induced plasma currents, called "bootstrap current" requires both high pressure and low plasma current. In order to accomplish this, both passive and active plasma control techniques need to be developed and incorporated into closed-loop feedback algorithms beyond their present state.

The fraction of self-generated "bootstrap" current, $f_{bs} \approx 0.02\ q\ \beta_N\ A^{1/2}$, is related to the plasma safety factor, q, the plasma aspect ratio, A, and the plasma pressure, characterize by the normalized pressure parameter, β_N. (See, for example, Zohm, et al., Nuclear Fusion 57, 086002 (2017) for discussion of these formula.) Shown in Figure 2.4, the fraction of self-generated "bootstrap" current reaches 100% when $\beta_N \approx 25/q$ for ITER parameters when $A = 3$. High bootstrap current fraction is a goal for efficient steady-state operational scenarios that require minimal injected current drive power. The TCV tokamak in Switzerland achieved 100% bootstrap current in 2008.[38] Passive control techniques use the stabilizing influence of image currents in conductors that are proximate to the plasma.[39,40]

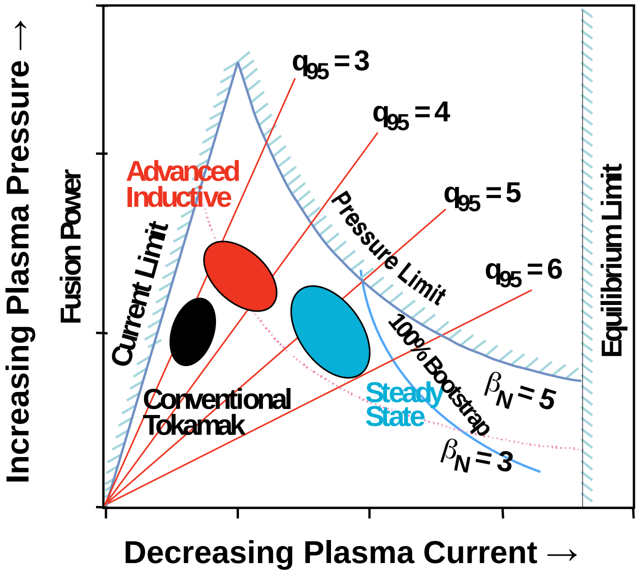

FIGURE 2.4 Stability requires plasma pressure and plasma current to be lower than limits shown above. The ITER baseline target is a "conventional tokamak." As the plasma current decreases, efficient "steady-state" operation becomes possible because the "bootstrap" current sustains the plasma without the need to drive current. SOURCE: Luce, *Phys. Plasmas*, 18, 030501 (2011).

Energetic Particle Physics

Burning plasmas will be self-heated by the α-particles (He^{++}) produced from fusion reactions. To date, only TFTR and JET operated with significant amounts of tritium to allow study of energetic α-particles. Both devices produced modest levels of fusion power, and the fraction of α-particle heating power to heating power supplied externally was low, between 10 and 15%. Burning plasma experiments in ITER are expected to achieve a fraction of α-particle heating power exceeding 60%.

Other fusion experiments without significant heating from fusion reactions do not generate an α-particle population; however, the energetic particle (EP) population created from neutral beam heating can serve as a proxy for the α-particles. Some present-day fusion experiments can produce an EP population that resides in the same "phase space" as that for the α-population expected in both ITER and a burning plasma produced in a more spherical configuration (see Figure 2.5). The EP phase-space is characterized by the fraction of energetic particle energy relative to the total plasma energy and speed of the EP motion relative to an Alfvén wave.

The dynamics of the EP population are governed by classical collisional processes in MHD-quiescent plasmas. A sufficient EP population, however, can drive instabilities, which can then interact with the EP population and affect performance through loss or redistribution of the energetic particles, leading to reduced plasma heating.

The past decade has seen significant progress in both understanding and mitigating the EP-driven instabilities in both stellarators and tokamaks.[41,42] Theory and numerical simulation advances have led to the development of models, validated by experiment, that predict the existence and characteristics of EP-driven modes, as well as their resulting interactions with the EP population itself.[43,44,45,46,47] This has allowed for accurate descriptions of their ability to heat the plasma and drive current. Presently, reduced models of the modes and their interactions are under development, and, along with reduced models of plasma transport and stability, will lead to a comprehensive physics-based capability for developing the

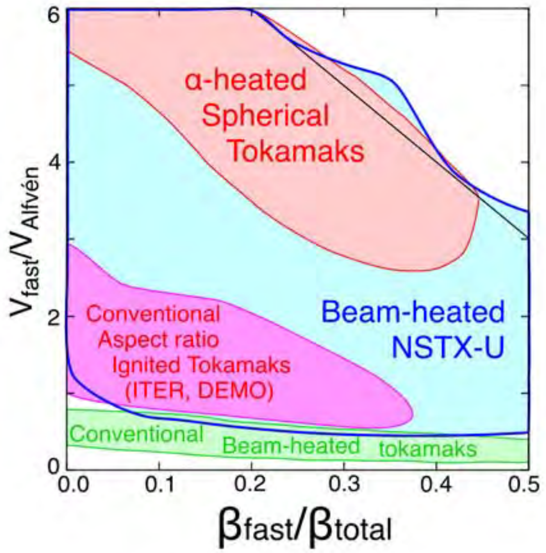

FIGURE 2.5 Energetic particle (EP) "phase space" for NSTX-U, present day higher aspect ratio tokamaks, and phase space regions expected for α-heated tokamaks at both low and high aspect ratio. SOURCE: Courtesy of E. Fredrickson and the Princeton Plasma Physics Laboratory.

operational scenarios necessary for ITER to achieve its Q = 10 target. Furthermore, this model development will leverage off of the success in mitigating EP-driven instabilities through "phase space engineering," in which neutral beam[48] and radio frequency wave[49] actuators are used to tailor the EP phase space in order to control the detrimental consequences of EP instabilities without compromising heating and current drive performance. These same actuators are planned for ITER.

While the tools and understanding that has developed over the past decade are sufficient for developing scenarios in which ITER can achieve its Q = 10 goal, only the study of the α-particle population generated by these burning plasmas will help ensure extrapolation from relative short-pulse fusion power production to one where α-particle modes can remain stable in long-pulse, steady-state operation.

Mitigation of Transients and Abnormal Events

Transients, or abnormal events, are phenomena that are short-lived and that release plasma energy at levels that can damage plasma facing components (PFCs). These phenomena include major disruptions and more localized plasma edge instabilities called Edge Localized Modes (ELMs).

Major disruptions are due to crossing into unstable operational space in current, density or β, or to technical system failures, and result in most of the plasma and magnetic field energy being released within thousandths of a second. The disruption can also result in a beam of relativistic electrons, which can cause highly localized damage to the reactor inner wall. While present devices are capable of handling these disruption loads, at least an order of magnitude increase in plasma and field energy content is estimated for ITER and future reactors, and therefore it is essential to develop reliable methods to avoid or mitigate disruptions to avoid damaging vessel components, to allow achievement of high fusion power density and to ensure continuous operation in a reactor.

Significant progress in disruption control has been made on three fronts: prediction, avoidance, and mitigation. Real-time descriptions of conditions that can lead to a disruption have been developed within empirical frameworks,[50,51,52] and these have led to predictability at or above the 95% level. For

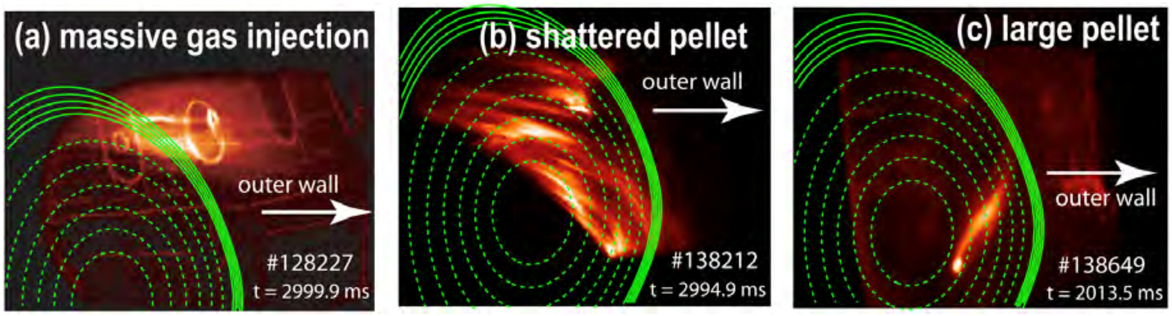

FIGURE 2.6 Examples of visible images from different rapid shutdown methods from DIII-D showing (a) massive gas injection, (b) shattered pellet injection, and (c) large intact pellet injection. Green curves are approximate plasma magnetic flux surface contours in tangency plane for orientation only. SOURCE: E.M. Hollmann, et al., "Status of research toward the ITER disruption mitigation system," *Phys Plasmas* 22, 021802 (2015).

early operations in ITER, predictability higher than 80% is required, although 98% disruption predictability is required at ITER's full operational capabilities.[53] Recent advances have included developing machine learning/neural network approaches,[54,55,56] real-time monitoring of plasma stability[57,58] and incorporating real-time stability calculations from reduced, physics-based MHD stability models to warn of an approach to stability limits.

If a disruption cannot be controlled or avoided, it would need to be mitigated, and progress to do this has been made using injection of gas, liquid and solid, which can cause high enough radiation to decrease the plasma energy content and provide high enough collisionality to inhibit the formation of runaway electron beams.[59,60,61] Shattered pellet injection, successfully developed on DIII-D,[62] has been adopted as the mitigation technique-of-choice for ITER. Demonstrations of post-disruption runaway electrons using shattered pellet injection (SPI) and massive gas injection (MGI) in the DIII-D experiment are shown in Figure 2.6. After injection of pure (100%) neon or argon atoms, total dissipation of fully avalanched runaway electron beams is achieved.[63] Novel methods, like shell-pellet injection,[64] have been demonstrated. Other methods to use radio frequency waves to dissipate runaway electrons have been proposed[65] that will be tested on DIII-D and could potentially be employed on ITER.

Edge Localized Modes, or ELMs, are features of H-mode plasmas in which the high edge pressure and pressure gradients cause intermittent edge instabilities that can release significant amounts of energy to the PFCs. The accompanying impurity influx from these material surfaces can lead to degradation of plasma performance. As with disruptions, present day devices are capable of handling the peak and averaged heat loads from ELMs, but even a 0.3% (~1 MJ) loss of thermal energy in ITER can lead to PFC damage.

A variety of mitigation methods have been developed and tested successfully on present-day devices. Three-dimensional edge magnetic fields have been applied to both mitigate and suppress ELMs[66,67,68,69] (see Figure 2.7). Repetitive injection of solid pellets was used to control the frequency of ELMs.[70,71,72,73] Deposition of lithium on the walls has been used to reduce the frequency of and ultimately eliminate ELMs.[74,75] Additionally, there are naturally occurring ELM-free regimes in which edge instabilities flush out impurities but preserve plasma performance,[76,77] and these regimes can be used as a basis for the optimized core-edge coupled operating scenarios in steady-state devices.

Fusion Technology and Engineering Science

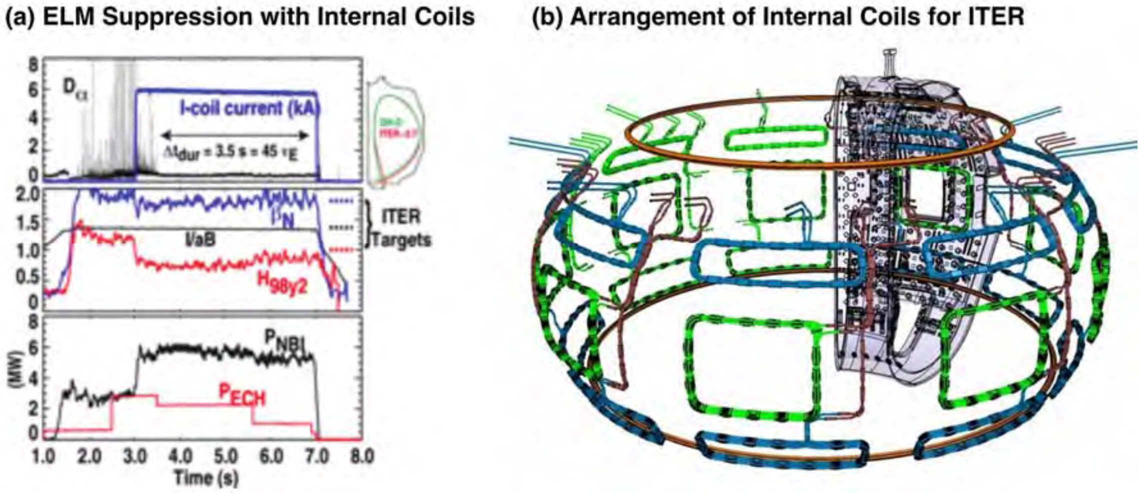

FIGURE 2.7 (a) DIII-D ELM suppression in an ITER Baseline-similar plasma using an applied magnetic field supplied by the I-coil. (b) Similar internal coils will be used in ITER. The ELMs (spikes in D_α in top panel) disappear when the external field is applied. SOURCE: Courtesy of M. Wade and General Atomics.

In addition to the scientific progress in the preparations for burning plasma operation in ITER, progress in fusion technology and engineering science has been significant. The fabrication of superconducting magnets (Figure 2.8), the ITER cryostat, and vacuum components are in progress. ITER has been licensed as a first-of-a-kind basic nuclear fusion facility. And ITER construction is now more than halfway completed to first plasma. Additionally, since the 2004 NRC Burning Plasma Assessment report,[78] fusion technology advances have been driven by ITER research needs and by next-step goals to fully enable the fusion energy system. Key contributions from the U.S. fusion technology program in recent years have led to successful progress in blanket research,[79] tritium and fuel cycle research,[80] fusion safety and environmental aspects,[81] remote handling approaches,[82] fusion materials science,[83] superconducting magnets,[84] and fusion energy systems studies.[85] These contributions have resulted from joint international projects in support of ITER and from tasks directed by U.S. researchers. Accomplishments include (but are not limited to) the development of vacuum and gas species management,[86,87] tritium fusion fuel cycle systems,[88] pellet injection for fueling and disruption mitigation,[89] and the manufacture of the ITER central solenoid.[90]

RESEARCH PROGRESS BEYOND ITER TOWARD FUSION ELECTRICITY

International research progress preparing for burning plasma study on ITER has also increased the state of readiness to undertake research beyond ITER leading toward the construction of follow-on devices that demonstrate fusion power production and the potential for economical fusion electricity. In Europe, Japan, South Korea, and China, research beyond ITER is directed to develop the interconnected science and technology needed to design and construct a device to demonstrate fusion power. Just as ITER has provided a research focus for international fusion researchers to advance burning plasma science, a strategy for the accompanying research and technology programs needed to progress beyond ITER to a commercial fusion reactor guides national research and innovation programs, helps to engage industrial partners, and sets national priorities.

(a) Installation of ground insulation at General Atomics

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FIGURE 2.8 (a) Ground insulation being applied to a central solenoid superconducting module at General Atomics (Poway, CA). The insulation must be precisely placed and consists of 18 layers of fiberglass, six layers of Kapton sheets totaling over 2,300 square meters, and a ground plane. (b) The ITER central solenoid will consist of six stacked modules, stand nearly 18 meters tall, and weigh more than 900 tons. When completed, it will be the largest pulsed superconducting magnet in the world.

Plasma Exhaust Physics

While temperatures in the core of the magnetically confined plasma can be up to 100s of millions of degrees K, the plasma cools as it is transported radially from core to edge through plasma transport, radiation, and other processes. Nevertheless, the edge plasma temperature can still be in the 10s of millions degree K range, and is much greater than the temperature that can be withstood by surrounding walls, for which there is an upper limit of ~1500 to 3000 K for most solid material to avoid melting.[91] Even at lower temperatures, the Plasma-Material Interactions (PMI) between the hot plasma and solid surfaces can cause drastic changes in the integrity of the wall material, notably through physical and chemical erosion. This can introduce impurities into the plasma, which can degrade plasma performance and fusion gain.[92,93,94]

There has been considerable progress over the last decade in mitigating heat fluxes escaping the plasma by various means that increase the area over which the heat is deposited. One such method is through plasma “detachment” from the divertor targets, obtained by additional gas fueling in the divertor region, which increases density and lowers the temperature of the plasma in the divertor region primarily through radiation.[95,96] Detachment can lead to factors of several decrease in the heat flux deposition without impacting the performance of the core plasma.

While detachment in a conventional divertor alone is estimated to reduce heat loading in ITER to an acceptable level by radiating 60-70% of the escaping heat flux, a next-step burning plasma may have heating and fusion powers greater than those expected in ITER, and with a conventional divertor, up to 90% of the heat exhaust would have to be radiated away to avoid material surface damage; at these levels, core plasma performance could be severely affected.[97] Studies of the compatibility of innovative divertor designs with divertor plasma detachment, which can significantly relax the radiated power requirement, are needed.

Innovative divertor designs use more complex magnetic topologies to spread the heat flux over a wider area on the target plates. This is done by increasing the field line length, which allows for additional cross-field transport of the heat, making the angle at which the field lines impinge on the surface shallower, and increasing the broadening of the magnetic field lines “tubes.” Innovative configurations that have shown heat flux reductions on a variety of devices include the Snowflake,[98,99,100] the X-divertor,

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FIGURE 2.9 Innovative divertor configurations may improve fusion power and particle handling. Shaping the magnetic field changes the nature of plasma interaction with the divertor armor and geometry, as shown with the colored lines used to trace magnetic field lines. SOURCE: Figure provided by H.Y. Guo and General Atomics and reprinted from "Magnetic Fusion Energy: From Experiments to Power Plants," ed. By G.H. Neilson, Woodhead Series in Energy, No. 99, Elsevier, 2016.

and the Small-Angle Slot divertor.[101,102] The Super-X[103] divertor is closely related to the X-divertor, and both will be studied on MAST-U[104] tokamak. Also related to the Super-X is the X-point target divertor concept.[105] These various innovative divertor configurations are shown in Figure 2.9.

Liquid metal (LM) surfaces are a potentially transformative solution to the heat flux challenge for all magnetic configurations, as the damage and/or erosion that can occur in solid PFCs are eliminated since the liquid metal walls are continually replenished with new, clean surfaces contacting the plasma. Liquid metals are renewable, and they return to equilibrium after perturbations. LMs can handle heat fluxes up to factors of several over the upper limits for solid walls.[106] One of the leading candidates for LM walls is lithium, which, when coated on solid walls through evaporation, led to improved confinement[107,108] and suppressed or mitigated ELMs.[109,110] Liquid lithium surface research and development on tokamaks is in the early stage[,111,112] and the challenges involve their design, stability in the presence of magnetic fields, retention of tritium (an issue for both liquid and solid walls)[113] and impact on plasma performance.[114,115]

Driving Plasma Current

Among the key challenges for obtaining a steady-state burning plasma beyond ITER is the capability to drive the plasma current non-inductively. This is of fundamental importance in tokamaks since tokamak confinement improves with the poloidal magnetic field that is produced by the plasma current. Efficient steady state operation in a tokamak requires operation in plasma regimes that yield significant self-driven (or "bootstrap") plasma current.[116] It is important that the self-driven current profile lead to a scenario that is stable to large-scale magnetohydrodynamic (MHD) instabilities.

The physics of externally produced non-inductive current drive (CD), from neutral beams (NB) and radio-frequency (RF) methods such as electron cyclotron (EC), lower hybrid (LH) and fast waves (FW) are now well understood and are documented in the ITER physics basis.[117,118] Recently, current drive by high frequency "helicon" waves has been proposed.[119] Most robust and free from accessibility issues are NBCD and ECCD. ECCD is particularly attractive since it can achieve the highest transmission power density, and the space necessary for power injection is smallest. Local current drive by ECCD can suppress internal MHD modes and the local ECCD is also effective for local pressure profile modification to further enhance plasma performance. The challenges facing ECCD include the relatively high cost of sources, the possible need for new source development if high fields are used, and the lower current drive efficiency for off-axis current generation which may be necessary for high bootstrap fraction. In contrast, LHCD already has readily available sources at lower costs and the off-axis current drive efficiency is perhaps the highest of any of the RF options. On the other hand, LHCD has important challenges because of the need for a close-to-the-plasma-edge launching structure.

Establishment of a high-bootstrap-current-fraction, fully non-inductive tokamak plasma at sufficiently high normalized-beta using reactor-relevant and efficient current drive systems is a critical research subject for developing steady-state scenarios and being able to operate in the reduced tritium breeding blanket space of a compact configuration.

Integrated Burning Plasma Configurations

Perhaps the greatest challenge faced in a burning plasma regime is the simultaneous solution to all of the above issues to achieve the overall goal of a fusion power system capable of uninterrupted operation. Measuring progress on multiple design metrics is not trivial. A number of the issues, including self-driven "bootstrap" current, external current drive and plasma heating systems, plasma-material interactions and power handling, and robust control and mitigation of transients, are to some extent measured by the normalized fusion gain (or triple product) and the duration of uninterrupted plasma confinement pulses. (See Figure 4.5 in Chapter 4.)

Burning plasmas must simultaneously achieve a high triple product while eventually being sustained for months of steady-state operation. Until now, short pulse experiments built with copper magnets have operated for several seconds and have achieved conditions equivalent to "scientific breakeven," or $Q \sim 1$, when extrapolated to operation with deuterium-tritium fuel. Longer pulse studies using experiments with superconducting magnets have been performed,[120,121,122,123] but these research devices are not large enough to operate at the high pressures needed for fusion gain. High power density scenarios capable of steady-state should be explored in actual reactor-like conditions, providing scientists the opportunity to study coupled electron-ion turbulence, super-Alfvénic ion distributions, and high opacity plasma edge. The highly non-linear interactions between different phenomena in fusion equivalent regimes, defined at reactor relevant integration parameters, have not yet been examined.

A critical integration aspect upon reaching fusion equivalent regimes is to reconcile the core and the edge. Because the plasma collisionality parameter, ν^* scales strongly with the ratio of plasma density to plasma pressure, $\nu^* \sim n^3 / P^2$, the parameters of both the divertor and the plasma core cannot simultaneously operate at reactor relevant parameters unless absolute reactor-relevant plasma pressure, P, is achieved. Because the plasma core and edge strongly interact, the core-edge-divertor interactions are altered by increasing neutral opacity as reactor-like densities are approached. As the fusion equivalent regime is approached, the divertor, scrape-off layer (SOL) and pedestal become increasingly opaque, and pedestal profiles become more strongly dependent on transport and pinch effects. Divertor and plasma confinement are linked, and integrated solutions require both regions to be in the relevant density regimes.

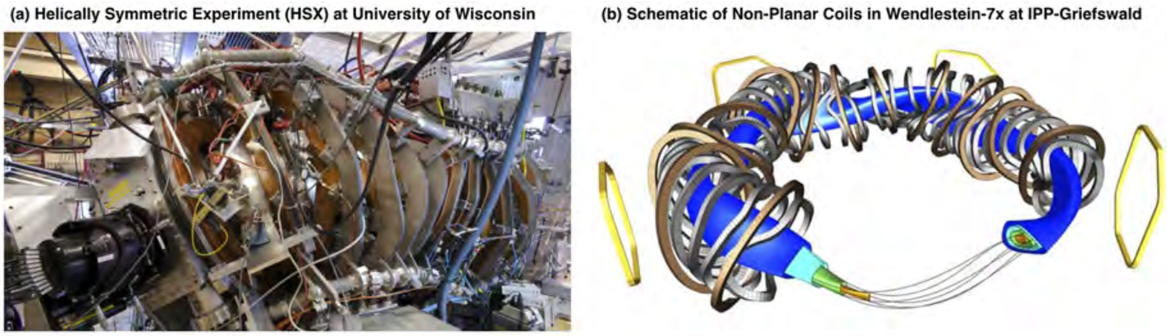
Another major issue is integrating the design and operation of tokamaks with requirements and technology imposed by future reactor engineering constraints. Progress toward this integration has been slow since plasma science and device performance are each a necessary first step. As devices approach the burning plasma regime it is appropriate to embrace design choices that are compatible with a future compact pilot plant. Notably, this includes operating with metal walls to minimize tritium retention, optimization of the geometry/topology of magnets, and measurement/control systems that can operate in a nuclear environment. In addition, the tritium breeding ratio and corresponding blanket design should be compatible with overall plasma performance.

Three-Dimensional Magnetic Fields and Stellarators

The study of very long pulse, toroidal magnetic confinement is underway using major research facilities using superconducting magnets. EAST (China), KSTAR (Republic of Korea), WEST (formally Tore-Supra, in France) are superconducting tokamaks, as is also ITER and the JT-60SA experiment under construction in Japan. The two superconducting stellarator facilities are the Large Helical Device (LHD) in Japan and the Wendelstein 7-X (W7-X) device in Germany. Because tokamaks and stellarators have strong magnetic fields and toroidal geometries, the fusion science and technologies of tokamaks and stellarators are similar. The fundamental dynamics of plasma confinement are described with the same methods; scientists produce and diagnose confined plasma using the same technologies; and tokamaks and stellarators are challenged to achieve and sustain the same fusion equivalent conditions.

Stellarators and tokamaks differ by the degree by which the magnetic field is three dimensional.[124] Tokamaks, like ITER, use relatively small three-dimensional magnetic field perturbations to control plasma instabilities, such as edge localized modes (ELMs), and influence plasma profiles and flows. (See Figure 2.7.) As the degree of three-dimensional magnetic field increases significantly, the usual confinement properties that arise from symmetry are broken and particle confinement requires carefully designed three-dimensional magnetic fields to avoid rapid particle loss. Careful design is also necessary for the three-dimensional magnetic fields used to control tokamak plasmas,[125] and this further motivates ongoing research linking the science of strong three-dimensional magnetic fields optimized for stellarators and the weaker three-dimensional magnetic fields needed to optimize performance of tokamaks, like ITER.[126]

Understanding transport in stellarators (Figure 2.10) has led to the design of a new class of stellarators that have recently commenced operating. Transport in early stellarators was dominated by collisional, or neoclassical, processes. Neoclassical effects cause the cross-field transport of otherwise trapped particles as well as large impurity fluxes, which can dilute the plasma and compromise performance. However, advances in theory and in numerical tools have led to identifying stellarator configurations with various optimizations of the magnetic field that predict a reduction in neoclassical transport to levels comparable to those in tokamaks.[127,128,129] The development of optimization codes have successfully designed of stellarators with reduced neoclassical transport.[130] A major new facility with such optimization, W7-X in Germany,[131] recently began operating, and experiments have confirmed the three-dimensional magnetic field optimization.[132] A prime goal of W7-X is to test fusion magnetic confinement for one such optimization scheme and the balance between neoclassical and turbulence-driven transport. The experiments will serve to validate results of several gyrokinetic codes, including the first fully global and physically comprehensive turbulence codes, which have recently been developed.[133]


(a) Helically Symmetric Experiment (HSX) at University of Wisconsin

(b) Schematic of Non-Planar Coils in Wendlestein-7x at IPP-Griefswald

FIGURE 2.10 Strong three-dimensional magnetic fields can create stellarators optimized to confine particles. (a) The HSX stellarator at the University of Wisconsin is the world's only quasi-helically symmetric stellarator. (b) The Wendelstein-7X stellarator in Germany is built from superconducting magnets in a configuration that minimizes equilibrium plasma currents.

Some MHD and energetic particles instabilities are predicted to behave differently in stellarators than in tokamaks. Understanding these differences will help to better control a burning plasma and to better predict fusion performance. For example, some stellarator configurations, like that used in W7-X, minimize the toroidal plasma current, and plasma current induced MHD instabilities can potentially be avoided. Other stellarator configurations, like the proposed National Compact Stellarator Experiment (NCSX),[134] are predicted to reduce the toroidal plasma current by more than half an equivalently sized tokamak. Because relatively few stellarators have been built and studied, stellarators provide new tests of our understanding of plasma stability limits. Although disruptions are absent in existing low current stellarators,[135] because high-pressure plasma confined within a quasi-symmetric stellarator are predicted to generate significant bootstrap current, current-driven instabilities and plasma current disruptions may need active methods for controlling the plasma profiles and mitigating the effects of transients just as in tokamaks. MHD-stability studies have been ongoing in LHD[136] and will be undertaken in W7-X and CTH.[137]

Stellarators also provide opportunities to investigate plasma heat flux issues and to better understand how to design an optimized divertor. Because the stellarator the configuration is intrinsically three dimensional, the design, maintenance and replacement of a stellarator divertor more complicated than in a tokamak while also providing an opportunity to validate three-dimensional models of the plasma edge and the plasma interaction with the first wall. There are several types of divertors that are being assessed on stellarators, including the helical divertor[138,139] and the island divertor.[140,141] Stellarator divertors have not been tested to the extent that they have been tested on tokamaks. Nevertheless, these challenges are common to both stellarators and tokamaks and include understanding the plasma boundary, including the effect of edge magnetic field shear, active control requirements and assessing compatibility of divertor solutions in a high-performance integrated core-edge coupled regime.[142]

Theory and Simulation at the Exascale

For many years, the U.S. effort in basic theory, simulation, and modeling of fusion plasmas has been extremely strong, with many U.S. scientists being recognized internationally as world-leaders in their respective fields. United States fusion researchers have been instrumental in driving recent, and seminal, progress in several diverse areas. Both analytic theory and reduced models and high-fidelity physics simulations development comprise this impressive set of accomplishments.

Theory and simulation offer important new opportunities for accelerating progress toward the objective of economical fusion energy development by incorporating recent advances in theoretical understanding, validated physics models, computing infrastructure, and diagnosis of experiments.[143,144] As described in the Report of the 2015 Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences,[145] what is needed is to comprehensively and self-consistently advance the many complex, nonlinear, and multi-scale plasma descriptions into an integrated suite of Whole Device modeling (WDM) capabilities.[146] The long-term goal of the project is to have a complete and comprehensive application that will include all the important physics components required to simulate a full toroidal discharge. Such a predictive modeling capability is required, e.g., for the interpretive analysis of existing devices as well as for minimizing risks and qualifying operating scenarios for next-step burning plasma experiments. In all future burning plasma facilities, the optimization of fusion performance and control scenarios will require predictive WDM with a quantified, validated uncertainty, as it will not be feasible to determine operational limits by running trial discharges.

The following research elements are critical for realization of a successful WDM capability:

- *Continued efforts to better understand and distill the physics of gap areas in fusion theory.* These gaps include understanding transients, the plasma boundary, fully non-inductive operation, and optimization of the toroidal magnetic configuration.
- *Increased development of and support for modular WDM frameworks.* A sustainable path forward will require support both for the most mission-critical legacy tools and for development and expansion of the newer efforts that can more effectively utilize leadership-class computing resources and execute next-generation work.
- *Increased connection to experiment through validation.* This will require the development and extensive use of tools that fulfill validation hierarchies and compute associated metrics, as well as an accurate and comprehensive set of diagnostics. Such an approach will require expertise in large-scale data management and analysis, including machine-learning strategies, for both leadership-class code output and the experimental observations against which they will be tested.

While present models can help develop operational scenarios for ITER and increase confidence in achieving its goals, a validated WDM capability would provide the confidence to explore the extreme parameter regimes of fusion reactors, informing decisions and lowering the future risks of building full-scale fusion power plants, and thus accelerating the fusion program.

Transformative Enabling Technologies

In addition to projects in support of ITER and domestic FES research activities, the fusion program can leverage technology developments in areas that have significant potential to advance fusion energy development. In order to capture the impact of such advances and identify ground breaking research opportunities for advancing fusion energy, the Fusion Energy Sciences Advisory Committee (FESAC) was recently charged “to identify the most promising transformative enabling capabilities (TEC) for the U.S. to pursue that could promote efficient advance toward fusion energy,” The FESAC TEC report[147] identified four areas of transformative enabling capabilities where, building from significant progress in certain areas of research, the U.S. has a strategic opportunity to develop transformative technologies to enable fusion energy. The four top-tier TECs identified by the panel were: advanced algorithms, high critical temperature superconductors, advanced materials, and novel technologies for tritium fuel cycle control.

Advanced Algorithms

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FIGURE 2.11 Importance of advanced algorithms is illustrated with (a) a “control operating map” for a burning plasma showing the level of controllability for several control parameters and (b) a schematic of the ITER disruption mitigation system (DMS) requiring off-normal fault response. SOURCE: Fig. 4.1.1 of Fusion Energy Sciences Advisory Committee Report on Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy, (2018)) and (b) J.A. Snipes, et al., “Overview of the preliminary design of the ITER plasma control system,” Nucl. Fusion 57 (2017) 125001.

Advanced control systems are required to control a burning plasma during the normal evolution of the plasma and, also, during transient events that need to be either predicted and avoided or mitigated. Advancements in feedback algorithms and intelligent systems may significantly improve the reliability of fusion power and perhaps enable operation at optimized operating points whose achievement and sustainment are impossible without high performance feedback control. As explained in the TEC Report, the area of advanced algorithms includes the related fields of mathematical control, machine learning, artificial intelligence, integrated data analysis, and other algorithm-based research and development. The importance of advanced algorithms is illustrated in Figure 2.11, which shows the variables and control functions in a fusion plasma “control operating map” and a chart illustrating the control function interactions for ITER's disruption mitigation system (DMS). As understanding of burning plasma operation improves, advanced control algorithms will support and accelerate the pace of physics understanding, enable the experimental realization of theoretically predicted operating scenarios, and build mathematical synergies with advances in other high-performance computing capabilities that will enable improved physics understanding. Machine learning and mathematical control can also help to bridge gaps in knowledge when these exist, for example to enable effective control of fusion plasmas with imperfect understanding of the plasma state.[148]

High Temperature Superconductors (HTS)

Advances in higher field superconductors present a major opportunity to enhance the performance and feasibility of fusion reactor designs. High-field, high-temperature superconductors would enable a new generation of relatively compact fusion experiments and power plants, dramatically speeding the development path and improving the overall attractiveness of fusion energy.[149] HTS technology could provide high energy gain and power density in much smaller devices, together with operational robustness and steady state potential needed for successful fusion energy. Strong magnetic fields are critical to the success of magnetic fusion as a source of energy. Achieving higher magnetic field strength extends the allowable plasma properties to higher plasma density, higher plasma current, and higher plasma pressure while retaining the same dimensionless scaling parameters found at lower magnetic field strength. This extended range of plasma parameters from high-field magnets allows more compact tokamak devices that may provide a lower cost path to future fusion reactors. ITER's superconducting magnet system will be the largest ever made and is designed to operate with the highest practical magnetic field strength for large toroidal field coils made of niobium-tin (Nb_3Sn) superconductors and consistent with the strength of steel.[150] New developments of rare-earth barium-copper-oxide high-temperature superconductors (Figure 2.11) may lead to larger magnetic field strength[151] and improved maintenance that potentially improve the prospects for economical magnetic fusion energy.[152]

Advanced Materials and Manufacturing

The behavior and integrity of materials in a fusion system are of great importance to the long-term viability of fusion energy.[153] The flux of energetic neutrons to the vessel and structural materials poses a serious materials problem that will require substantial testing, some of which may be done on a burning plasma experiment. The high energy neutrons from the D-T fusion reaction generate between 50 to 100 times higher He/dpa in materials such as ferritic steels than does fission reactor irradiation. Burning plasma experiments will thus aid in the development of high-heat-flux components and will serve as testbeds in which to evaluate the performance of the components in a reactor-like fusion environment.

The heat loads on components in a burning plasma experiment will be comparable to those expected in a reactor and will require the application of state-of-the-art high-heat flux technology using materials that satisfy requirements of tritium retention, safety, structural integrity, lifetime, and plasma compatibility.[154]

Since the 2004 NRC Burning Plasma Assessment report, the United States has made significant advances in fusion materials studies, including contributing to the qualification of reduced activation ferritic martensitic steels for the European demonstration fusion reactor,[155] nanostructured[156] and oxide dispersed strengthened steels,[157] all aspects of SiC/SiC technology,[158] and new understanding of tungsten[159] and tungsten composites[160] as fusion plasma-facing materials. Linear plasma simulators allow for long-duration study of material evolution under fusion-relevant plasma flux, but they are not useful to test integrated plasma-material effects expected in fusion divertors. In the United States, linear plasma simulators include the PISCES facility at University of California, San Diego,[161] the Tritium Plasma Experiment (TPE) at Idaho National Laboratory (INL) (Figure 2.12), and the Material Plasma Exposure Experiment being developed at Oak Ridge National Laboratory.[162]

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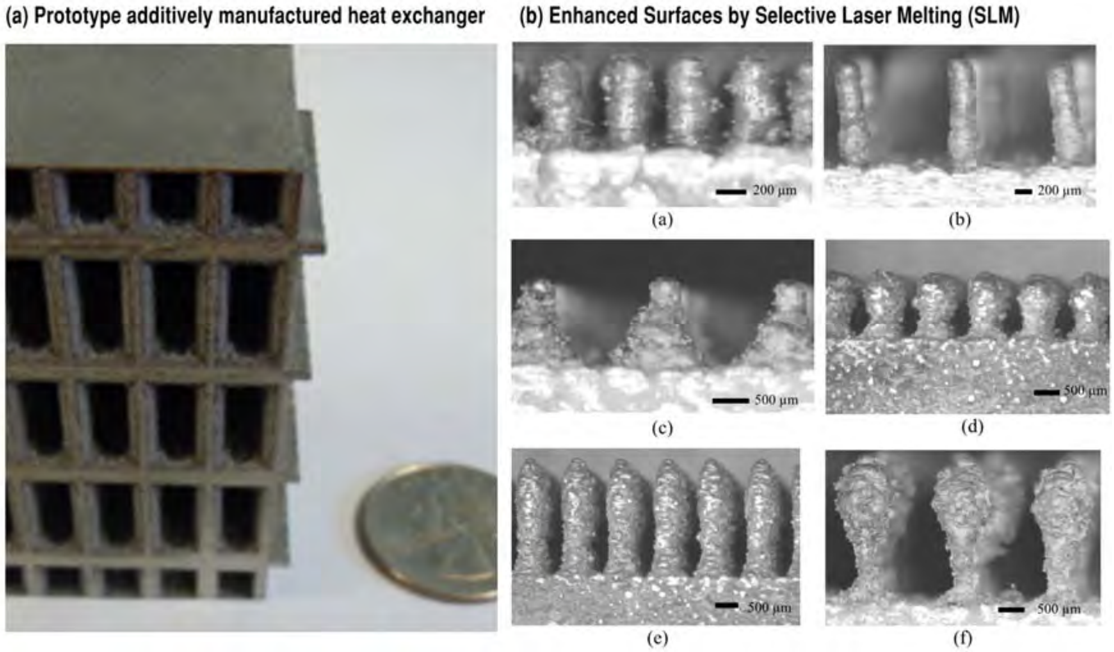
FIGURE 2.12 Photograph of Yttrium-based high-temperature superconducting tape from Fujikura, now routinely manufacturing wires with critical current densities greater than 3 MA/cm^2 and production rates of 10-100 meter/hour.

Qualification of materials to operate safely in a fusion environment is of critical importance moving forward. Material effects have to be strongly connected to any consideration of availability, reliability and maintainability of the fusion core. All of these have a large impact upon the three overarching factors of plant economics, public perception and ability to license.


(a) Prototype additively manufactured heat exchanger

(b) Enhanced Surfaces by Selective Laser Melting (SLM)

FIGURE 2.13 Advanced manufacturing used for enhanced heat exchanger structures. Left (a) shows a prototype tungsten heat exchange structure with 3D surfaces. Right (b) shows a variety of enhanced surfaces made with selective laser melting (SLM). See review by Davoud Jafari and Wessel W. Wits, The utilization of selective laser melting technology on heat transfer devices for thermal energy conversion applications: A review, *Renewable and Sustainable Energy Reviews* 91 (2018) 420–442.

Looking toward future opportunities, new material designs and processes will enable the realization of resilient components that are essential to survive the harsh fusion environment and to optimize the reactor's performance. As reported by the 2018 U.S. DOE FESAC Committee on Transformative Enabling Capabilities, "Advances in novel synthesis, manufacturing and materials design are providing for some of the most promising transformation enabling technologies in PMI and nuclear fusion materials to enable fusion energy for the future."[163] The novel features enabled by advanced manufacturing and additive manufacturing include complex geometries and transitional structures, often with materials or constituents including hard-to-machine refractory metals; the potential for local control of material microstructure; rapid design-build-test iteration cycles and exploration of materials and structures for containing and delivering liquid metals. The U.S. Department of Energy's first Manufacturing Demonstration Facility[164] is located at ORNL and is developing new manufacturing technologies beneficial for fusion energy technologies. These include advanced metals manufacturing: electron beam melting, laser-blown metal powder deposition, laser sintering, and metal laser melting. Figure 2.13 shows an example of selective laser melting (SLM) for complex manufacturing of enhanced tungsten heat exchangers. With these emerging techniques, important new opportunities are emerging to develop the resilient materials and components for a fusion energy system.

Fusion Blanket Research and Tritium Fuel Cycle

A fusion 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 needed for the development of fusion energy. Fusion reactors should operate with more tritium produced and recovered than is burned. The vast majority of the fuel injected in a fusion chamber will not be burned in a single pass. Unburned deuterium-tritium fuel will be continuously transported to the plasma edge, where it will be exhausted, stripped of impurities, and then reinjected into the plasma. A burning plasma experiment provides the opportunity to test and evaluate the performance of prototypical blanket modules and demonstrate technologies for tritium extraction from blankets and for fuel processing systems that can be operated efficiently at large scale.[165,166,167]

Some recent successful activities in the U.S. include construction and operation of the MaPLE (Magnetohydrodynamic PbLi Experiment) facility[168] international blanket research partnerships (e.g., Korean National Fusion Research Institute (NFRI)-UCLA-INL collaboration framework and UCLA-EUROfusion collaboration), and innovative ideas in the tritium fuel cycle.[169,170] In particular, significant progress has been made in experiments and massively parallel simulations to understand magneto-hydrodynamic flows of liquid metal, self-cooled, dual-coolant, and helium-cooled lead-lithium blanket concepts.

It is well recognized that the development of a fusion breeding blanket is an outstanding challenge for fusion because scientific gaps exist related to controlling tritium permeation and minimizing tritium inventory.

While the 2004 report of the NAS Burning Plasma Assessment Committee noted the central role of the ITER Test Blanket Module (TBM) in the United States fusion research program, the U.S. is not a partner in the ITER TBM Project, nor will the decision to incorporate TBMs on ITER be made until much later in the ITER construction schedule. While the signing of all of the TBM Arrangements (TBMA) occurred in 2015, the TBM preliminary designs are not expected until 2023. The final TBM designs are not expected until 2025, and the first installation of the TBMs will occur after 2030. Because the decision to install TBM on ITER will not be made until after additional legal arrangements are signed dealing with all TBM phases through decommissioning,[171] the careful consideration for the best approach to advance fusion tritium blanket technology could include becoming a supporting partner with a TBM activity along with other approaches.

The recent FESAC TEC[131] report recognizes this challenge, and identifies several opportunities to develop technologies with potential to address existing gaps, such as novel blanket technologies for tritium breeding that allow for higher thermal to electrical efficiencies and improved tritium breeding ratios (TBR).[172,173] advanced tritium extraction technologies,[174] and new fuel recycling technologies that allow for minimization of tritium inventories.[175]

Fusion Safety

A burning plasma experiment offers the opportunity to begin development of the technologies needed for a fusion reactor, including important safety-related technologies. Many components and systems needed for fusion's safety objectives are unique, such as source diagnostics and cleaning technologies, state-of-the-art safety analyses tools, technologies for the remote handling of large activated components, technologies for the control of routine tritium releases, and innovative approaches for the control of tritiated and mixed waste streams.[176] A burning plasma experiment will be an integrated demonstration of the safety, reliability, and effectiveness of these technologies.[177] In the United States, recent progress has been remarkable in the areas of safety code development and understanding of tritium behavior in fusion systems.

INL's Safety and Tritium Applied Research (STAR) facility is a worldwide unique facility capable of handling tritium and radioactive materials, as well as other controlled chemical elements such as beryllium and lead.[178,179] This facility provides opportunities for researchers to investigate the synergistic effects of hydrogen isotopes in neutron irradiated fusion materials at burning plasma operating conditions. Experiments at the STAR Facility include the Tritium Plasma Experiment (TPE), the Tritium Gas Absorption Permeation (TGAP) Experiment, the Neutron Irradiated Material Ion Implantation Experiment (NIMIIX), and the Experimental Chamber for Evaluation of Exploding Dust (ExCEED). Recent progress has allowed researchers to expand the understanding of tritium permeation and retention behavior in tungsten at prototypical fusion conditions. Not only have the number and types of traps been measured, but also how these crucial safety parameters vary with neutron irradiation history and temperature. In addition, excellent progress has been made in the area of safety code development. The MELCOR for fusion and Tritium Migration Analysis Program (TMAP) codes[180] developed at INL, have been used for safety analyses in licensing ITER and design studies for many national and international future fusion reactors. These computer codes are in use at more than 30 fusion institutions worldwide and have recently been merged allowing for tritium tracking within a fusion facility during normal operation and accident conditions.

Integrated Systems Engineering for Fusion

Integrated systems studies guide research and identify programs that can reduce cost and lower risk to the development of fusion power. Integrated systems studies combine burning plasma science, materials science, fusion nuclear science, and systems engineering to evaluate safety, environmental and maintainability issues, and technical requirements to progress toward fusion energy. Recent progress in systems engineering studies in the United States and by our international partners have had an enormous impact on the direction of research to address fusion economics, public perception and regulatory framework.

Systems engineering combines plasma physics and engineering constraints into a self-consistent integrated design for large-scale fusion facilities. Systems engineering studies have been carried out for various types of fusion reactors, including the advanced tokamak,[181] high-field tokamak,[182] and the spherical tokamak and stellarator.[183] The United States has made significant progress in the area of fusion nuclear systems study,[184] leading to the definition of requirements for a Fusion Nuclear Science Facility (FNSF)[185] for integrated testing of fusion components. Figure 2.14 illustrates several examples of integrated systems studies, ranging from a pilot plant that would generate 73 MW of net electricity to a large commercial demonstration facility generating up to 300 MW of net electricity, operating without interruption, and designed with sufficient cooling for 1.5 GW of fusion power production. These systems engineering and integrated fusion systems studies are the primary means to combine the knowledge obtained from burning plasma study with the interdisciplinary sciences needed to define the most optimal path toward fusion energy demonstration.

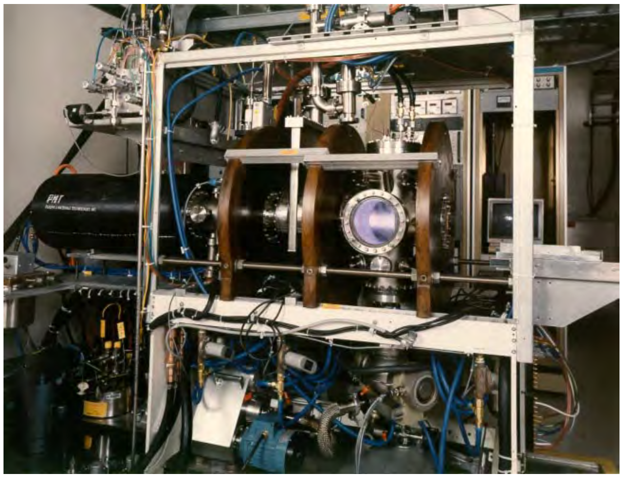


FIGURE 2.14 Tritium Plasma Experiment (TPE) at Idaho National Laboratory is a linear plasma device to accelerate deuterium and tritium plasma ions into metal target samples. TPE test samples are first irradiated at the High Flux Isotope Reactor at ORNL to simulate fusion neutron damage and then exposed to deuterium and tritium to evaluate promising materials for use in fusion divertors.

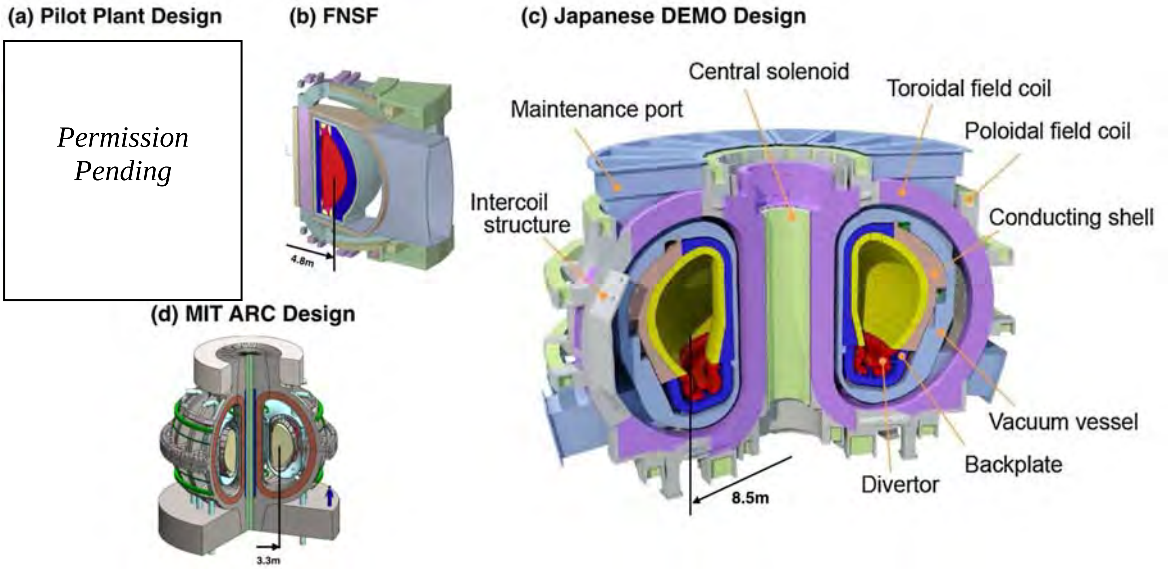


FIGURE 2.15 Example next-step options resulting from integrated systems studies in the United States and in Japan. Each study combined burning plasma science with different engineering constraints and assumptions for large superconducting magnets. Integrated systems studies guide research and identify programs that can reduce cost and lower risk to the development of fusion power. SOURCE: (a) J.E. Menard, at al., Nuclear Fusion 56, 106023 (2016), (b) C.E. Kessel, et al., Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.06.003, (c) Kenji Tobita, et al., Fusion Engineering and Design (2018), https://doi.org/10.1016/j.fusengdes.2018.04.059, and (d) B.N. Sorbom, et al., Fusion Eng Des 100, 378 (2015).

SUMMARY

Since the United States joined the ITER partnership, experiments using research facilities in the United States and in other nations have been highly productive. New ideas to control and sustain a burning plasma have been discovered, and theoretical and computational models developed in the United States have substantially improved the ability to control plasma stability, predict plasma confinement, and enhance fusion energy performance. Methods to control and mitigate transients and scenarios that will guide operation of ITER have been successfully tested. The understanding of burning plasma science has advanced significantly.

> **Finding:** The U.S. fusion energy science program as part of the international research effort has made leading advances in burning plasma science and technology that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.

Although the primary focus of the world's fusion research program is the preparation for ITER experiments, progress has also resulted in the research aimed beyond ITER to address remaining science and technology challenges and demonstrate innovative solutions that lead to a reduced size, lower cost, full-scale power source. While this research is much less developed than the science and technology required for a burning plasma experiment, opportunities exist to increase the readiness to benefit from ITER experiments and progress toward the demonstration of economical fusion power. New technologies, such as high-field superconducting magnets, may reduce the size of next-step fusion demonstration experiments. Advances in understanding and predictive models also suggest that opportunities exist to pursue more compact follow-on experiments.

> **Finding:** In addition to burning plasma studies, further research in burning plasma science, fusion nuclear science, and fusion materials science is needed to reduce the cost and fully enable the fusion power system.
>
> **Finding:** New technologies for fusion, advances in understanding and predictive modeling, the improved confidence in the science and operation of ITER, and the engineering systems studies conducted both within the United States and by our international partners demonstrate a readiness to undertake the research leading to a cost-effective next step toward the realization of commercial fusion energy.

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3

Extending the Frontier of Burning Plasma Research

This chapter describes the importance of burning plasma research, explains why continued participation as an ITER partner is important to United States fusion energy research, and describes how ITER participation will inform the design of a compact fusion pilot plant as a new element of the United States magnetic fusion program. While decades of international collaborative research have been spent establishing confidence in the science and technology basis for reliable pulsed operation in ITER, a compact fusion pilot plant requires extending the burning plasma regime beyond ITER and achieving uninterrupted operation having simultaneously high normalized confinement, high fusion power density, and a long-life divertor and first-wall. Because the physics basis of the compact fusion pilot plant is less mature than the physics basis for ITER, hands-on experience and study of a burning plasma experiment, like ITER, will be essential along the path forward to the U.S. compact pilot plant.

This chapter begins with a brief summary of the committee's Interim Report assessment of the importance of burning plasma research to the development of fusion energy and of the ongoing activities of the United States that supports burning plasma science and the ITER project is included. Next, research activities that will maximize the benefits from U.S. participation in ITER and advance the science and technology needed to reduce risks in the design and operation of a compact fusion pilot plant are presented. Chapter 3 concludes with three findings and with two recommendations for how the U.S. DOE FES should conduct both the near-term and long-term ITER research. Chapter 3 also includes two findings describing research needs if the U.S. withdraws from the ITER project and states the committee's recommendation that the United States should not withdraw. However, if the United States does withdraw from the ITER partnership, the U.S. DOE/FES should still initiate a plan leading toward the construction of a compact fusion pilot plant. In the scenario without ITER, an alternate means to study a burning plasma and to engage the international community would be required.

THE IMPORTANCE OF BURNING PLASMA RESEARCH

The importance of a burning plasma experiment as a required step in the development of practical fusion energy has been endorsed by all previous strategic planning documents prepared for the United States fusion research program.[1] As ITER partners, the fusion research programs of the United States and other nations have focused on preparations for the study of burning plasmas using the ITER experiment for more than a decade.

Access to a burning plasma in ITER will open a new frontier in science. For the first time, scientists will observe the complex processes of a plasma that is primarily heated by the energetic particles created by fusion reactions within the plasma itself. Even beyond the observation of a self-heated fusion plasma, the study, control, and manipulation of a burning plasma in ITER will give scientists their first opportunity to demonstrate many technical capabilities needed by any energy-producing magnetic fusion device. ITER will extend the frontier of burning plasma research to include opportunities to learn how to sustain a fusion plasma for durations much longer than previously achieved and how to maximize the fusion power produced from a burning plasma. The frontier of burning plasma research also leads to progress in the applied and engineering sciences needed to design reliable structures that surround the plasma and provides the first opportunity to gather materials data needed to design systems that convert fusion energy into useful heat and power. In all of these ways, the science learned from study of burning plasma in ITER will extend beyond ITER and contribute to the engineering science of large fusion energy facilities and contribute to the applied science of predicting, controlling, and sustaining a magnetically confined burning plasma.

The committee's Interim Report reaffirmed the importance of burning plasma research to the development of fusion energy, as well as to plasma science and other disciplines. Furthermore, because ITER is the only existing project to create a burning plasma at the scale of a power plant and also a major component of the U.S. fusion energy program, the scientific and technical goals of ITER give clear illustration of the importance of burning plasma research. ITER will demonstrate the scientific and technical feasibility of fusion energy for peaceful purposes. The ITER target is to sustain high fusion power gain ($Q \sim 10$) for more than five minutes and to provide the capabilities to study advanced operating scenarios and explore a wide range of fusion confinement parameters. Long plasma durations exceeding 15 minutes are planned that will be useful for limited nuclear testing of tritium blanket modules. For shorter durations, ITER will test advanced scenarios with elevated plasma pressure and higher fusion power output that may allow investigation of ignited or near ignited burning plasmas. These ITER research targets are ambitious, but the understanding of burning plasma science has advanced significantly and the international effort to prepare for ITER operation has further increased confidence in the burning plasma performance that can be achieved in ITER. As explained in Chapter 2, this is due to the discovery of new ideas to control and sustain a burning plasma, the substantial improvements in the ability to predict plasma confinement and fusion energy performance, and the demonstration of burning plasma scenarios that are expected to simultaneously satisfy the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components.

The importance of burning plasma research to the development of fusion energy is described below in two parts: (1) understanding and controlling a burning plasma and (2) advancing fusion technology and engineering science.

Understanding and Controlling a Burning Plasma

Burning plasma experiments in ITER will address critical research areas and answer key scientific questions, including:

- A burning plasma experiment will represent the first time that a confined fusion plasma is dominated by fusion-born alpha particles. Energetic alpha particles from fusion reactions heat and sustain the burning plasma, but they are also predicted to drive plasma instabilities. While the onset of energetic particle instabilities is understood, detailed identification of nonlinear mechanisms is just beginning. Beyond understanding energetic particle dynamics, important research opportunities include methods to control energetic particles instability for helpful purposes such as favorably modifying the current profile or to govern the nonlinear dynamics to control fusion burn.
- A burning plasma experiment advances understanding of plasma transport properties from the core to the boundary. Although there has been considerable progress made in predicting plasma transport, the validity of these predictions need to be tested in future burning plasma experiments. In particular, confinement studies using a burning plasma will help determine confinement scaling in desirable fusion reactor conditions characterized by high plasma beta, steady state, and compatible divertors. In addition, transport of plasma impurities eroded from material surfaces, as well as helium produced by fusion reactions, are not yet understood. ITER experiments will give scientists a first look at heat and particle transport at the scale of a fusion power plant.
- A burning plasma experiment enables critical tests to control plasma transients. Due to the large energy of a burning plasma, transient events, which cause rapid energy loss from the plasma, may damage first-wall materials. Transients include plasma current disruptions and edge localized modes, called "ELMs." The United States has led the world in the development of techniques for understanding, as well as predicting, avoiding and/or controlling plasma transients. These techniques are critical for ITER and other burning

plasma devices, and ITER will provide a critical test of disruption avoidance and mitigation systems at reactor scale and power density.

- A burning plasma experiment advances divertor science necessary for a fusion power source. Unless controlled, the power escaping from a burning plasma will lead to inner wall damage. Control of escaping heat and particles is made by carefully shaping the magnetic field so that plasma flows along the plasma boundary and into a divertor, where the plasma heat and particle flux can be nearly extinguished by interaction with recycling neutrals. The U.S. research program has significantly advanced understanding of burning plasma boundary physics, including improved understanding of the narrow "scrape-off layer" connecting the confined plasma to the divertor[2] and the successful testing of innovative divertor concepts.[3] However, further developments for a divertor with long lifetime remains a major fusion research challenge, and ITER will enable detailed tests of divertor physics, including detachment, retention, erosion and re-deposition in reactor-like conditions.
- A burning plasma experiment tests integrated scenarios that simultaneously test the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components needed for a fusion energy source. Plasma operation and control scenarios have been developed and tested in preparation for ITER experiments, and integrated models using the latest advances in high-performance computing now routinely interpret experimental measurements and make progress in predicting the results of burning plasma experiments. Additionally, the U.S. research program has led the world in the development of quiescent plasma scenarios not subject to damaging transient events, which can achieve the same plasma performance at reduced plasma current and so minimize the risk of disruption damage. A burning plasma experiment can also test other advanced scenarios, like the so-called "super H-mode," which represents an attractive area of innovation aimed to reduce the size of a fusion device with improved confinement. An ITER research program focused strongly on advanced scenarios and physics model validation will enable an advance in understanding needed to develop an attractive, compact fusion pilot plant.

Advancing Fusion Technology and Engineering Science

As an ITER partner, the United States receives full benefit from the technology developed for ITER. Because U.S. industry is fabricating major systems for ITER, burning plasma research is also building industrial capacity in fusion nuclear science, superconducting magnet engineering, nuclear instrumentation, and plasma heating and control systems. Construction and operation of the ITER facility addresses important research in fusion nuclear science and engineering science, including:

- *Fusion fuel processing, blanket design, and tritium breeding.* The release of fusion energy results from the fusion reactions of tritium and deuterium ions heated to 100 million degrees. While deuterium is abundant, tritium will be produced from lithium within a fusion breeding blanket, which is a key fusion nuclear technology needed for the development of fusion energy. Tritium for ITER will be obtained from the tritium removal facility of the Canadian-owned Ontario Power Generation (OPG) utility using tritium produced within CANDU nuclear power stations. The vast majority of the fuel injected in a fusion chamber will not be burned in a single pass. ITER will provide the first opportunity for large scale fuel processing of deuterium-tritium, which will be transported continuously from the plasma edge, then exhausted from the vacuum chamber, stripped of impurities, and reinjected into the plasma. ITER will also provide the first opportunity to test and evaluate the performance of prototypical blanket modules and demonstrate technologies for tritium extraction from blankets in ITER test blanket modules.[4,5]

- *Fusion safety, remote handling, and waste management.* As a burning plasma experiment, ITER will provide the first opportunity to begin development of the technologies needed for a fusion reactor, including important safety-related technologies. Many components and systems needed for fusion's safety objectives are unique, such as source diagnostics and cleaning technologies, state-of-the-art safety analyses tools, technologies for the remote handling of large activated components, technologies for the control of routine tritium releases, and innovative approaches for the control of tritiated and mixed waste streams.[6] ITER will be the first integrated demonstration of the safety, reliability, and effectiveness of these technologies.[7]
- *Fusion materials science.* As a burning plasma experiment, ITER will aid in the development of high-heat-flux components and will evaluate the performance of the components in a fusion environment at the scale of a power plant. The heat loads on components in a burning plasma experiment will be comparable to those expected in a reactor and will require the application of state-of-the-art high-heat-flux technology using materials that satisfy requirements of tritium retention, safety, structural integrity, lifetime, and plasma compatibility.[8,9,10] Additionally, the behavior and integrity of materials irradiated by fusion neutrons are of great importance to the long-term viability of fusion energy.[11] The high flux of energetic neutrons to the vessel and structural materials poses a serious materials problem that will require substantial testing, some of which will be done on ITER.[12]
- *Plasma heating and current drive systems for fusion.* Plasma heating by electromagnetic waves and neutral particle beams are needed to heat the plasma to a burning state,[13] sustain plasma current,[14] modify temperature and current profiles, and control plasma instabilities.[15] Fusion reactor research continues to push the frontiers of high-power mm-wave and radio-frequency technology, and these technologies will be extensively tested at the reactor scale on ITER.[16]
- *High-field magnet technology for fusion.* Strong magnetic fields are critical to the success of magnetic fusion as a source of energy. Achieving higher magnetic field strength extends the allowable plasma properties to higher plasma density, higher plasma current, and higher plasma pressure while retaining the same dimensionless scaling parameters found at lower magnetic field strength. The superconducting magnets being constructed for ITER will be the largest ever made and are designed to operate with the highest practical magnetic field strength for large toroidal field coils made of niobium-tin (Nb_3Sn) superconductors and supported by steel.[17]Experience operating ITER's superconducting magnets will advance physics understanding of the role of magnetic field in a burning plasma and inform the development of large-scale superconducting magnet technology.

As the world's first burning plasma experiment at the scale of power plant, ITER will provide scientists the first opportunity to access the frontier of burning plasma research. The complex processes within a burning plasma that couple plasma confinement, energetic particles created by fusion reactions, plasma stability, and fusion materials and technologies will be investigated. Because ITER is built at the scale of a power plant, ITER offers the first opportunity to begin development of nearly all of the technologies needed for a fusion reactor. In addition, as the first licensed fusion research facility, within the licensing code requirements used by the French nuclear industry, the safe operation of ITER will demonstrate necessary safety and operational procedures of a fusion power system.

THE IMPORTANCE OF ITER TO THE U.S. FUSION RESEARCH PROGRAM

Burning plasma research in support of ITER and in preparation for ITER experiments is a primary focus of the fusion research programs of the United States and other nations. Preparation for ITER experiments is a central element of today's burning plasma research activities. Participation in the

ITER project also provides formal mechanisms for U.S. scientists to take leading roles in the international effort to develop fusion energy and to benefit significantly from international collaboration. Because the United States is a key contributor to ITER construction, participation in ITER has resulted in significant advances in U.S. domestic industrial capabilities and capacities that would not have happened without ITER participation.

The important role of ITER in the U.S. fusion research program is described below. First, the U.S. role in ITER construction is discussed and the resulting benefits to the United States in industrial capabilities. Next, advances in fusion technology resulting from U.S. participation in ITER are presented. Finally, research in preparation for ITER experiments provides a focus for ongoing burning plasma research that has already resulted in substantial scientific progress in understanding, predicting, and controlling a burning plasma.

United States Partnership in ITER Construction

In December 2017, the ITER project passed the construction milestone of having completed 50% of the tasks required for first plasma operation. ITER is a large and ambitious facility. The fusion containment vessel, superconducting magnets, and cryostat will weigh 23,000 metric tons. The largest superconducting magnets are the poloidal field coils with a 24 m diameter. Each of 18 superconducting toroidal field coils is 17 m tall, weighs 360 metric tons, and will be installed to a precision of less than 0.1 mm in the radial plates which support the large magnet forces.

Since the 2013 ITER Management Assessment Report,[18] the new director, Bernard Bigot, has played a key role in enacting rigorous project discipline in a nuclear project culture, enabling milestones to be met consistently. Project decision processes and accountability have been substantially improved through improved integration of the ITER Central Team and the domestic agencies. Component design is now finalized, and a new optimized resource-loaded schedule has been developed to minimize the time to first plasma. Since 2016, all scheduled project milestones have been achieved on schedule. The recently revised *ITER Research Plan*[19] has a first plasma in 2025, first scientific experiments in 2028, and a first burning plasma experiment with deuterium and tritium fuel in 2035. The ITER Organization now has a team of over 800 people, of which 5.5% come from the United States, with many thousands working on the construction site and in the globally distributed supply chain.

The external structure surrounding the tokamak is now largely complete, as is the assembly hall standing 60 m tall and with a crane lifting capacity of 1500 metric tons. The ITER cryo-plant will be the largest single platform cryo-cooling facility in the world. It will distribute liquid helium to various machine components, including the superconducting magnets, thermal shield, and divertor cryopumps. The last of eighteen skids supporting the helium compressors was installed atop its massive four-meter-high concrete pad in November 2017. The 400 kV switchyard to provide power from the grid has been successfully installed and commissioned. Many ancillary heating and diagnostic buildings are now erected and awaiting fit out.

A 12,000 m^2 facility has been built to wind the largest poloidal field coils since they are too large to be transported to the site. The first two poloidal field coils are now being wound and all the superconducting strand is now on-site. The 30 m x 30 m cryostat is being assembled on site and undergoing final welding. General Atomics has completed the first module of the 1000 metric ton central solenoid, which will produce ITER's highest magnetic field of 13 T. Besides initiating plasma current within ITER, the currents in the six modules of the central solenoid will be independently controlled to shape and position the plasma.

The United States has committed to contributing 9.09% of ITER's construction costs. Participation in ITER in this fashion has resulted in significant advances in U.S. domestic industrial capabilities and capacities, with the vast majority (approximately 80 percent) of U.S. ITER construction funding remains within the U.S. supply chain.[20] For example,

- The United States has proven its capability for fabricating superconductor in bulk, producing over four miles of cable-in-conduit superconductor for the toroidal field magnets;
- The United States is fabricating a first-of-a-kind 13 m tall, 13 T central solenoid electromagnet, which is unique worldwide and has required the development of bespoke fabrication and testing infrastructure;
- United States industry is developing microwave and radio-frequency transmission lines to provide unprecedented power transfer for heating in ITER;
- High-throughput cryogenic pellet fueling systems and tritium processing systems have been developed by U.S. national laboratories; and
- Instrumentation for the fusion nuclear environments has been developed.

In addition, the United States has been tasked with the research, design and fabrication of the AC power system (delivered), the tokamak cooling water system, the vacuum pumping systems and the tokamak exhaust processing system. The United States has also been a key contributor toward the approval of ITER's license to start construction, by providing a "pedigreed" version of the fusion-modified safety code MELCOR, developed and maintained by the Fusion Safety Program at INL, which has been used extensively for the safety analyses presented to the French Nuclear Regulator (*Autorité de Sureté Nucléaire*) as part of the Construction Authorization Request.

According to the DOE project execution plan for ITER,[21] the United States has "made considerable progress in completing its assigned hardware design, R&D, and fabrication work." Final design of about two-thirds of U.S. hardware is complete, and two of thirteen in-kind hardware systems have been delivered. A total of $942 million has been obligated by the U.S. ITER project with contracts spread across U.S. industry, universities, and national laboratories, across 44 states.[22] Approximately 50 U.S. personnel are working as members of the staff of the ITER International Organization (IO). More than one hundred full-time equivalents (FTEs) are working in the U.S. ITER Project Office, with most on the central solenoid construction and tokamak cooling water system. It is anticipated that with full funding, approximately 150 FTEs will be working in the U.S. ITER Project Office. The technical leadership and contributions made by the U.S. fusion science team is and will continue to be important to the eventual success of the ITER design, operation, diagnostics, and analyses. In addition, the U.S. financial commitment is highly leveraged by the sharing of costs and technology with its international partners. The performance of the United States in its ITER obligations has been very favorably assessed by the U.S. Government Accountability Office[23] and DOE assessments and quality assurance audits conducted in 2015.

The U.S. contribution to ITER construction is a prime driver for the U.S. fusion technology program, and the United States is contributing a number of key systems that are both important for ITER and for any future fusion power system. U.S. ITER participation has the effect of not only providing leadership in the field of fusion technology, but also building capability in United States industry and capacity to provide components for future fusion experiments and facilities. The United States has several critical items to deliver for the completion of ITER construction and it should remain committed to delivering these key systems.

U.S. Research in Support of ITER Burning Plasma Science

The International Tokamak Physics Activity (ITPA) operates under the auspices of ITER, and the ITPA provides an international framework for coordinated fusion research useful for all fusion programs and for broad progress toward fusion energy. The United States continues to make significant contributions to the ITPA, which coordinates the international tokamak physics research and development activities and provides the physics basis for the ITER project. Presently, the United States chairs four of the seven ITPA Topical Working groups. The United States also actively participates in multiple-facility, joint tokamak experimental exercises. For example, joint experiments coordinated among MAST, ASDEX Upgrade, and DIII-D have recently evaluated the use of resonant magnetic field perturbations and pellet injection to suppress edge localized modes (ELMs)[24] leading to the introduction of ELM control systems to be tested in ITER.

Ongoing advances in understanding burning plasma physics enable improvements in the prediction and optimization of ITER and in future burning plasma experiments. Progress has resulted by combining physics-based dimensionless analysis with the development and validation of advanced physics models using high-performance scientific computing. While this approach increases confidence in ITER performance, the burning plasma regime is an extrapolation of fundamental underlying processes. The normalized size of a burning plasma experiment is much larger than in existing devices, and this may alter the confinement and stability properties. Heating and current sources, including the fusion alpha particles that will heat a burning plasma, will involve new science. Finally, the boundary of the burning plasma, where atomic physics and interaction with material surfaces become important, may lead to new phenomena.

While addressing all these issues self-consistently awaits a burning plasma experiment, there are numerous opportunities to establish the physics basis for optimal fusion performance. These include: (1) exploring plasma confinement physics expected in ITER, especially core plasma energy transport, plasma edge pedestal physics, and the transition between low-confinement (L-mode) and high-confinement (H-mode), (2) exploring the strongly coupled physics of a burning plasma regime when fusion alpha particle heating interacts with plasma transport and stability; (3) optimizing methods to control ITER plasmas to reach performance targets, maintain stability and avoid or mitigate transients and disruptions; and (4) further development and validation of plasma-material-interaction theory and simulation, leveraging advanced computational techniques and next generation exascale computers.

Integrated understanding of the plasma core-edge integration with the materials science of the divertor and first-wall is an ongoing research area that will benefit burning plasma experiments in ITER and contribute to United States efforts toward an attractive compact fusion pilot plant. Because the core and edge plasma are guided by different physics, bringing the two together in high fusion performance, reactor-relevant scenarios represent a grand challenge of burning plasma science. Doing so will enable validation of theory and simulation in a reactor relevant physics regime, while qualifying exhaust scenarios at relevant heat loads. Core-edge integration requires high plasma pressure in order to simultaneously achieve the high particle density needed for attractive exhaust solutions, while maintaining reactor-relevant low plasma collision rates. Experimental investigation of core-edge integration will also need to address the conflicting needs for a cold, dense divertor to avoid material erosion and, simultaneously, a hot, high power density core for high fusion performance. ITER will provide a critical opportunity to explore a high-power density core at reactor-like dimensionless parameters, combined with a tungsten divertor.

As United States fusion researchers approach and access frontier studies of the burning plasma state, additional research topics provide opportunities for progress. These include:

- Disruption mitigation research, including development of prediction and avoidance algorithms using passive and active control as well as mitigation (*i.e.* shattered pellet Injection, SPI);
- ELM control through pellet injection, applied external magnetic perturbations, natural ELM-free regimes;
- Controlling heat exhaust through detached divertor and innovative divertor configurations
- Development of ITER-relevant steady-state, non-inductive high-performance scenarios with acceptable divertor power loading;
- Development of predictive computational tools within integrated simulations enabling extrapolation to ITER regimes, including models for non-inductive current drive, core

confinement, pedestal physics, core-edge coupling, energetic particle-induced instabilities, plasma transient control, and plasma surface interactions;
- Development of integrated frameworks for plasma control algorithm development;
- Understanding material properties under the combined load condition and neutron loading present in ITER with verification of models against irradiated samples from test reactors; and
- Understanding the redistribution and loss of energetic particles and how Alfvénic instabilities can be mitigated in burning plasmas.

U.S. Contributions to Fusion Technology

Fusion technology advances have been driven by ITER research needs and by next-step goals to fully enable the fusion energy system. ITER provides important experience for the critical development of fusion technology and engineering needed in a fusion power device. Examples include: operation of superconducting magnets, tritium handling systems, and tungsten divertor performance. Key contributions from the U.S. fusion technology program involve the fusion fuel cycle, fusion materials, fusion materials modeling,[25] fusion plasma power handling, superconducting magnets, and liquid metals. These contributions have resulted from joint international projects in support of ITER and from tasks directed by U.S. researchers. Examples include vacuum and gas species management,[26,27] tritium fusion fuel cycle development,[28] pellet injection for fueling and disruption mitigation,[29] and the manufacture of the ITER central solenoid.[30] The capabilities of the United States pellet injection technology will be used in future fusion experiments at the JET device (see Figure 3.1).

Many of the program advancements in fusion technology and engineering science in the United States are coordinated with the Virtual Laboratory for Technology (VLT). The VLT functions as a "virtual" laboratory with many collaborating institutions within the United States, including eight universities, nine national laboratories, and one private company.[31] The VLT facilitates fusion technology and engineering science in the United States by (1) developing the enabling technology for existing and next-step experimental devices, (2) exploring and understanding key materials and technology feasibility issues for attractive fusion power sources, and (3) conducting advanced design studies that provide integrated solutions for next-step and future fusion devices and call attention to research opportunities in the field.[32] As was described in Chapter 2, the United States has also advanced the science of high-power plasma-material interactions using linear plasma simulators.

Preparing for ITER's Scientific Mission

Research preparation for ITER's scientific mission has focused on science and technology needed to extend ITER operation for long pulse durations and to provide safe, reliable operation of the machine for long duration pulses. Research results in support of ITER's scientific mission also support the scientific missions of fusion energy facilities that will follow ITER. Three active research areas are: controlling the high heat flux on the divertor, preventing or minimizing transient edge instabilities that could damage the divertor armor, and preventing or mitigating an uncontrolled loss of plasma confinement, called a plasma current disruption, that could damage the first wall or the vessel structure. Significant progress in all three of these areas were described in Chapter 2.

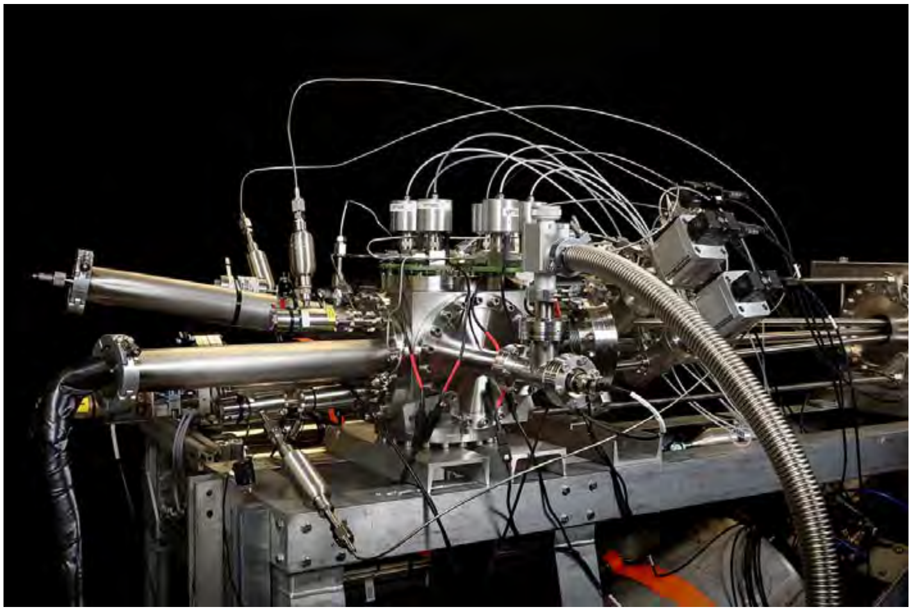

FIGURE 3.1 Shattered pellet injection components for ITER's disruption mitigation system were tested first at ORNL before shipment to the UK's JET tokamak for further testing. Photo courtesy: U.S. ITER/ORNL. For this JET application, the ORNL injector is compatible for operation with tritium.

The large heat flux to the divertor is determined, in part, by the width of the channel in which hot plasma escapes the confined plasma region and is directed to the divertor region. The ITER design can accommodate a peak heat flux of 10 MW/m^2. This heat flux is achieved by operating the divertor in a "detached" or "partially detached" state where the majority of the escaping plasma heat flux is radiated by recycling neutral atoms in the diverter region. Detached divertors have been achieved on a number of devices worldwide, and the science of the escaping plasma heat flux continues to be an active area of research.[33,34]

The baseline operating scenario for ITER is high-confinement (H-mode) with a strong edge transport barrier and high pedestal pressure. The steep pressure gradient at the H-mode pedestal can destabilize Edge Localized Modes (ELMs). However, experiments on a number of devices worldwide have demonstrated that it is possible to suppress or mitigate the effects of these ELMs by either applying non-axisymmetric magnetic fields locally to the plasma edge, or injecting small pellets at high-frequency. These control schemes are now included in the ITER design.

Finally, ITER will have the largest plasma current ever produced in a magnetic confinement device, and an unmitigated plasma current disruption has the potential to significantly damage first-wall components and divertor armor. To mitigate the effects of disruptions, ITER is planning to use massive injection of gases and injection of shattered pellets to provide injection of a substantially larger volume of particles than is in the fuel, which will radiate the stored energy across all of the material surfaces, thereby mitigating any risk of damage. These techniques to mitigate disruptions have been demonstrated, notably in DIII-D, and will soon be tested in JET using the Shattered Pellet Injector (SPI) anticipated for ITER (see Section II.1.b). Following a recent disruption mitigation workshop,[35] the U.S. is actively participating in an ITER Disruption Task Force and exploring even more effective techniques for disruption mitigation.

EXTENDING ITER PERFORMANCE

Recent advances in validated theory and simulation provide opportunities to significantly extend ITER performance, including higher fusion power gain, longer plasma duration, demonstration of advanced operating scenarios, and improvements in divertor power handling. Simulations of integrated

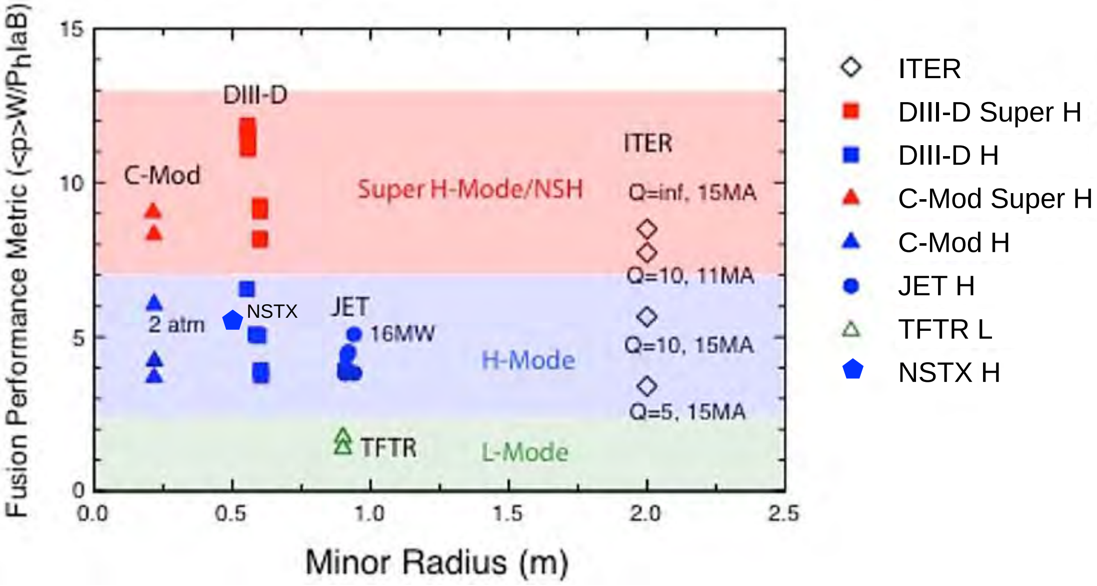

FIGURE 3.2 Metric of fusion performance based on the product of volume averaged pressure (<*p*>) and stored energy (*W*) divided by the product of heating power (P_h), current (*I*), minor radius (*a*) and magnetic field (*B*), is plotted in units of kPa MJ / MW MA m T. Experiments on DIII-D and Alcator C-Mod have sustained values of this metric sufficient for ITER to meet its goals and have briefly achieved higher values (red symbols) yielding enhanced ITER performance. SOURCE: Adapted from Snyder et al., "High Fusion Performance in Super H-Mode Experiments on Alcator C-Mod and DIII-D," 27th IAEA Fusion Energy Conference, Paper EX/2-4 (2018).

core-pedestal performance have already been used to optimize steady-state scenarios on DIII-D[36] and make initial predictions for ITER.[37] New high-performance regimes such as Super H-Mode have been predicted first, and later experimentally confirmed. These optimized regimes resulted in the highest plasma pedestal pressure (p_{ped} ~ 80 kPa) ever achieved in a magnetic fusion device using the Alcator C-Mod tokamak,[38] and the demonstration of the highest value of peak fusion gain, (Q_{equiv} ~ 0.5), ever achieved on a medium-scale ($R < 2$ m) tokamak by operating with advanced scenarios on DIII-D.[39] These achievements are summarized in Figure 3.2.[40]

Existing medium-scale and large-scale fusion experiment have achieved performance levels consistent with ITER's goals and have briefly achieved normalized performance levels that would enable ITER to exceed its fusion performance goals. These might allow high fusion power gain (Q ~ 10) at lower plasma currents and fusion ignition, or near ignition, which corresponds to achieving both high plasma confinement and high fusion power. Achieving and sustaining these levels of performance in ITER would represent a significant development toward smaller, less costly, compact fusion power systems. Figure 3.2 highlights these achievements using two metrics of fusion performance: the plasma pedestal pressure and a new metric motivated by recent advances in simulation $<p>W/P_hIaB$. This is a metric of fusion performance based on the product of volume averaged pressure (<*p*>) and stored energy (*W*) divided by the product of heating power (P_h), plasma current (*I*), minor radius (*a*) and magnetic field (*B*), and is plotted in units of kPa MJ / MW MA m T. The normalized plasma pressure is β_N; the average plasma pressure is given by $<p>$ (Pa) = 4000 β_N ($B\ I/a$); and the plasma energy confinement time is W/P_h. In this way, the fusion performance parameter, $<p>W/P_hIaB$, measures both high plasma pressure and high plasma confinement relative to the provided plasma current, field and minor radius. High performance has also been demonstrated relative to empirical H-mode confinement scalings.[41]

Existing devices such as DIII-D and NSTX-U provide opportunities to address key science that may extend the fusion performance in ITER. These include continuous operation while avoiding transients, maximizing normalized core performance at high bootstrap fraction, and developing exhaust solutions. Collaborations with the European JET experiment on the planned D-T campaign should prove very valuable for validating physics models in high performance core plasmas consistent with an ITER-like beryllium wall and tungsten divertor. Collaborations with EAST and KSTAR, and in the future JT-60SA, enable model testing in long pulse mode. JT-60SA in particular provides a compelling opportunity to test model predictions made in advance of an experiment, as will be necessary in ITER. US-developed models such as EPED and TGLF have been applied in initial predictive studies of JT-60SA, and these models, coupled to others, can be applied in comprehensive predictions of performance and performance optimization in JT-60SA, which can then be tested as the machine enters high power operation.

Improvements in high performance computing hardware and algorithms, including the advent of exascale computing, also provide an opportunity to extend the fusion performance of ITER. During the next few years, advanced scientific simulations will be able to incorporate higher resolution time and space scales and explore the complex couplings between electrons, ions, and global collective plasma physics. Advances in analytic theory, including development of new formalisms capable of efficiently treating the full range of scales associated with both magnetohydrodynamics and gyrokinetics, will lead to improved study of the boundary plasma where equilibrium and turbulence scales overlap. A comprehensive theory and simulation program including high fidelity multi-scale simulations, reduced models incorporating insight from those simulations, and very fast neural net interpolations of more complex models will enable theoretical understanding to be involved in all aspects from experimental planning, to control, design and optimization of the fusion concept. Integrated simulation, moving toward whole device modeling by connecting physics models from the core to the pedestal, boundary, and material interface, provides a timely opportunity for comprehensive planning of burning plasma experiments on ITER.

Continued physics model development and validation using the results from United States facilities, DIII-D, NSTX-U, and the international experiments will further increase confidence in ITER predictions. Additionally, experiments using U.S. facilities can develop advanced scenarios, closely guided by validated models, to enable high fusion performance in both inductive and steady-state scenarios. In particular, advanced scenarios, such as the “Super H-mode,” are expected to be achievable on ITER[42] and lead to important studies of enhanced fusion performance in ITER and improved confidence in the design of the compact pilot plant.

The United States has also contributed to the development of steady-state scenarios, where the plasma current is largely self-driven, through the “bootstrap” effect, and does not rely on inductively driven current. A strong focus on high performance steady-state scenarios on ITER will also advance understanding of the high-performance steady-state plasma, where the heating source (primarily fusion produced alpha particles) and current drive (primarily pressure-driven bootstrap current) are both strongly coupled to confinement and energetic particle physics.

Understanding Plasma Confinement at the Scale of a Power Plant

The move from existing fusion experiments to experiments at the scale of a power plant, like ITER, brings important changes to the underlying plasma and atomic physics. The ratio of the ion gyroradius to the device size, called ρ^*, will be much smaller than on existing devices. This is true because the reactor’s minor radius, *a*, is larger, the magnetic field is relatively stronger, and the gyroradius decreases with magnetic field. Numerous physical processes in both the core and edge plasma are expected to have important dependencies on ρ^*, and in some cases these dependencies are still not well understood.

In addition, a fusion device at the scale of a power plant is influenced by the atomic processes associated with the fueling and penetration of neutral particles at the plasma edge. In existing magnetic confinement experiments, the neutrals penetrate a significant distance into the pedestal region of the confined plasma, and the pedestal region is directly fueled by recycling neutral atoms, which are ionized upon penetrating into the plasma. This neutral penetration depth relative to the width of the pedestal is denoted by λ*, which scales roughly in proportion to the inverse product of plasma density and plasma size. However, the large scale and relatively high density of a device like ITER prevent neutral penetration into the pedestal region. The study and understanding of plasma confinement processes under conditions of small ρ*, short neutral penetration depth λ*, and high plasma pressure and fusion power density is a scientific frontier of burning plasma research.

Pedestal Physics at the Power Plant Scale

High confinement regimes are necessary for high fusion gain in ITER and in compact fusion pilot plants. These regimes are characterized by stabilization of plasma turbulence and radial shear of the plasma flow near the pedestal. The increased plasma confinement associated with the high-confinement operating mode, called the "H-mode," occurs when the plasma shear flow is self-generated near the edge pedestal region. How the turbulence suppression and plasma confinement properties scale with decreasing ρ* is an important question to answer at the scale of a fusion power plant. Because the plasma flow shear stabilization takes place across a region which scales with the turbulent eddy size, there is no significant ρ* scaling of the pedestal width in front-propagation paradigm. To date, observations on existing devices in carefully controlled dimensionless experiments have found no significant ρ* scaling of the pedestal width.[43] However, it remains to be learned whether ρ* physics may enter at very small ρ* values which may impact the pedestal pressure in ITER and other future fusion power devices. Ongoing model tests on existing devices,[44,45] particularly at higher field, can shed light on this and further extend comparisons such as that shown in Figure 2.2(b). Detailed testing of physics models in the early stages of ITER operation should improve understanding before entering the burning plasma phase of ITER. The role of direct fueling by neutrals in determining the pedestal density and density profile also plays an important role. An ongoing series of high-density experiments on DIII-D is currently exploring this physics, and experiments on ITER will provide critical data.

Predicting the L-H Transition

The physics associated with the initial formation of the edge transport barrier (known as the "low-to-high" or L-H transition) remains poorly understood. Empirical scaling of the heating power required for the transition suggests high power will be needed in an ITER-scale device because the needed L-H power is observed to increase strongly with magnetic field, density, and plasma surface area at an aspect ratio of $A \sim 3$. Being able to predict the L-H power threshold precisely is important for development of high-performance scenarios on ITER. Both the empirical scaling and some proposed physics models, such as those that include the role of ion orbit loss,[46] suggest ρ* scaling. In addition, changes in fueling and recycling, such as divertor leg length, have been observed to affect the L-H transition, suggesting a role for neutral penetration physics. Results from NSTX suggest a possible collisionality dependence. Three-dimensional (3D) fields, such as those ITER plans to use to control ELMs, also are known to impact the L-H transition. Ongoing studies on existing devices such as DIII-D and NSTX-U can further explore the role of geometry, fueling and 3D fields on the L-H transition. The early operation phase of ITER, including operation at reduced field to reduce the L-H threshold power, will provide valuable data to further develop physics understanding, and burning plasma experiments on ITER will address L-H transition physics at high power density and reactor-like physics parameters.

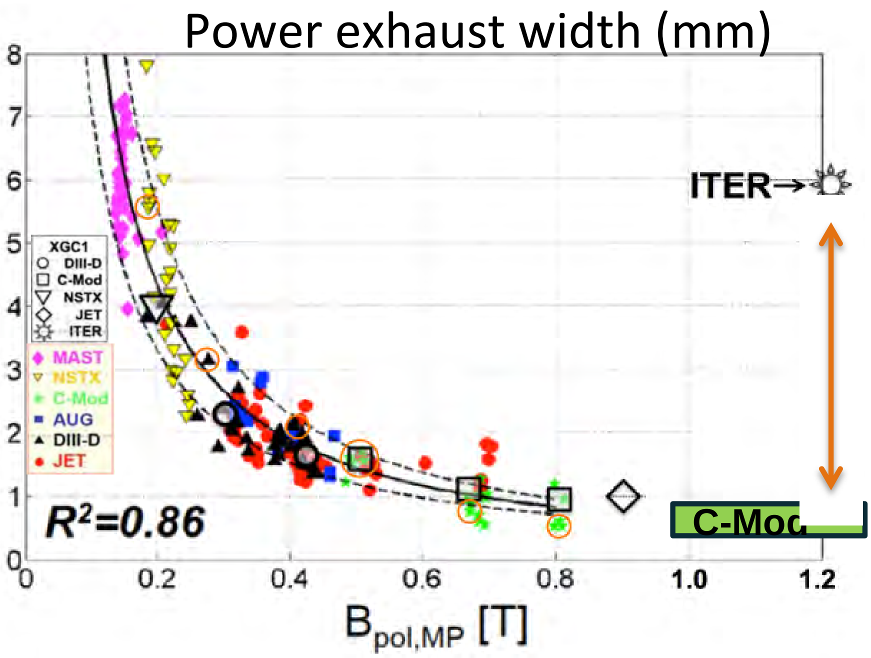

FIGURE 3.3 Observations of the power exhaust width (SOL) decreasing as the inverse of the poloidal magnetic field, $B_p \propto AB/q$. Adapted from T. Eich et al, "Scaling of the tokamak near the scrape-off layer H-mode power width and implications for ITER," 2013 Nucl. Fusion 53 09303, with the addition of recent plasma simulation results showing the electron-scale turbulence will widen the power exhaust width in ITER, from C.S. Chang et al, "Gyrokinetic projection of the divertor heat-flux width from present tokamaks to ITER," 2017 Nucl. Fusion 57 116023.

Understanding the Plasma Power Exhaust Width

As heat leaves the confined plasma it is quickly lost to the divertor across a narrow layer known as the scrape-off-layer width, λ_q. As shown in Figure 3.3, observations of the scrape-off-layer width shows that it scales inversely with the poloidal magnetic field, or $\lambda_q \propto q/AB$, where q is the plasma safety factor (inversely proportional to the twist rate of the magnetic field), A is the plasma aspect ratio, and B is the magnetic field strength. At high q or low magnetic field, λ_q is wide and spreads the escaping plasma heat across a wider surface within the divertor. In contrast, at low q or higher magnetic field, λ_q becomes narrow and the peak power dissipation in the divertor region increase. Empirical scaling of λ_q suggests it narrows with increasing poloidal magnetic field, and may therefore be very small, as small as 1 mm in ITER.[47] Physics models based on drift scaling also predict narrow λ_q for ITER.[48,49] However, physics models incorporating micro-instabilities suggest that as ρ^* gets smaller, gradients across the scrape-off-layer will become high, strongly driving turbulence which transports heat radially, broadening λ_q.[50,51] These models predict much larger values of $\lambda_q \sim 5$ to 8 mm for ITER. A similar broadening is predicted for high plasma current (2 MA) NSTX-U plasmas, and validation of these calculations on both NSTX-U and ITER can lead to a full understanding of this important physics at reactor scale.

Core Heat, Particle, Momentum and Impurity Transport

In the plasma core, the competition between turbulent and neoclassical transport is expected to be strongly affected by ρ^*. In particular, transport of high Z impurities such as tungsten are often dominated by the neoclassical pinch in existing devices, but turbulent transport is predicted to play a much more important role in ITER.[52,53] ITER is also expected to operate much closer to the critical gradient for micro-instabilities which has important effects requiring large scale, long duration simulations to explore.[54] Low ρ* is also predicted to weaken coupling between equilibrium and turbulent eddy scales, making transport more local. The physics of momentum transport, and the mechanism for generation of so-called intrinsic rotation, are relatively poorly understood, and ITER results at low ρ* and low injected torque will clarify important physics. In addition, ITER will operate with a variety of hydrogen isotopes, including protium, deuterium, and tritium, and so will provide important data on the isotope effect on transport.

Density Limit

Tokamaks are observed empirically to encounter a density limit that scales roughly with the ratio of the plasma current to the square of the minor radius.[55] The physics mechanism for this density limit is not well understood, though a number of theories have been proposed, such as the radiative island theory.[56] On existing devices, the plasma density limit is also associated with high collisionality in the plasma edge. However, at the high pressure expected in ITER, it should be possible to encounter the density limit at low collisionality, providing insight on the role of plasma collisionality in density limits. This physics is very important for ITER and reactor performance, because state-of-the art performance projections predict that fusion performance increases with density even to densities above the empirical limit observed in present devices.

Alpha Particle Transport

Fusion plasmas contain energetic ions created by fusion reactions in the plasma. In present devices, energetic ions can be produced by injecting beams of high-energy neutrals into the plasma that, after ionization, subsequently heat it; alternatively, radio frequency waves accelerate an energetic ion population. In a fusion power device, fusion reactions between deuterium and tritium produce energetic alpha particles (also known as the nuclei of helium gas) at 3.5 MeV. The alpha particles are trapped within the plasma and heat the plasma and sustain its temperature. Besides heating the plasma, the energetic ions may drive instabilities that degrade their confinement. At their worst, alpha-particle instabilities may cause beams of energetic ions to be lost to the first wall and erode wall materials. Figure 3.4 illustrates the orbit of an energetic ion in the DIII-D device that resonates with a 115 kHz Alfvén eigenmode. Even if the ions remain in the plasma, their radial redistribution can degrade plasma performance. Near-term research concentrates on acquiring the ability to predict which instabilities will be unstable, the non-linear coupling among multiple simultaneous modes, what their consequences will be, and developing methods to mitigate adverse consequences. Reduced models and high-fidelity physics simulations using high-power computing play a key role. Development of simpler models that are less expensive computationally enable efficient prediction and model validation. Experiments on both DIII-D and NSTX-U will help to validate these simulations. Experiments on ITER are a vital step in developing confidence in these projections at reactor scale. One difference between ITER and present-day devices is that the energetic-particle orbit is a smaller fraction of the machine radius. This is predicted to change the spectrum of unstable waves, which may alter their saturation mechanism. Using neutral beams, these predictions can be tested in the non-nuclear phase.

A major goal of ITER is to study the behavior of alpha particles, for the first time, in plasmas with dominant fusion-product heating. The plasma will be a highly coupled, nonlinear system, as changes in alpha confinement will alter the heating profile which may, in turn, alter the production of alpha particles. High power deuterium-tritium experiments in ITER constitute a crucial experimental test of our ability to predict alpha-particle behavior in a power plant.

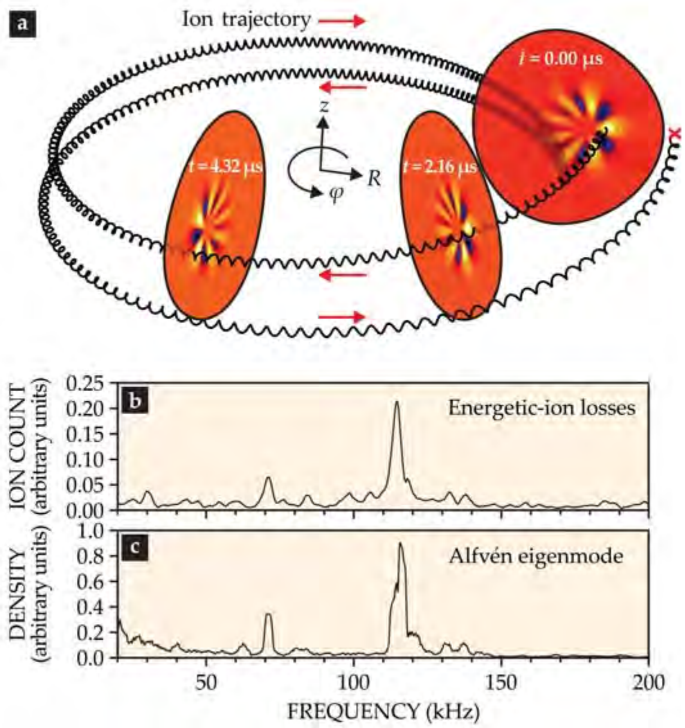

FIGURE 3.4 The evolution of an ion interacting with an Alfvén eigenmode as measured in the DIII-D tokamak. In (a), an ion trajectory is shown in resonances with the spatial and temporal structure of the global Alfvén eigenmode. The interaction leads to a large displacement of the resonant ion, and eventually the ion ends at a location marked x, where a sensor detects it outside the plasma. Power spectra from fluctuations of (b) energetic-ion losses and (c) plasma density measured reveal peaks at the eigenmode frequency of 115 kHz. SOURCE: David Pace, W.W. Heidbrink, and M.A. Van Zeeland, "Keeping fusion plasmas hot," *Phys Today* 68, 34 (2015).

Exploring and Controlling a Burning Plasma

A burning plasma is a highly coupled, nonlinear system. The energy and momentum that alpha particles provide to the plasma will affect the plasma current, transport, and stability in a manner that will alter the density and temperature of the burning fuel, which, in turn, changes the rate of fusion reactions. Achieving and controlling the burning plasma state involves understanding these internal nonlinear couplings and the self-organized plasma configuration resulting from self-heating. A burning plasma is fundamentally different from plasmas that have been created in all research facilities to date, and ITER will provide the first opportunities to study, sustain, and control a burning plasma.

In preparation for ITER experiments, many techniques to control the coupled plasma state can be explored beforehand. Couplings between the current profile, transport properties, and macroscopic stability are already operative in existing experiments. In general, plasma control hinges on three elements: sensors that measure the plasma state, actuators that alter the plasma state, and algorithms that direct the actuator response to the sensor input. In the case of plasma control, the goal is often to suppress an instability or, if that is not possible, to mitigate its impact. Instabilities that can damage the first wall of the plasma chamber include plasma current disruptions, edge localized modes (ELMs), neoclassical tearing modes (NTM), and Alfvén eigenmodes. Exploration of these instabilities benefit from the development of new sensors and instrumentation that can be operated in the radiation environment of a burning plasma, testing of control actuators, such as localized microwave heating, and the development of new control algorithms and real-time control systems.

DEVELOPING AN ALTERNATE APPROACH WITHOUT ITER PARTICIPATION

Previous sections of this chapter describe the importance of burning plasma research, explain why continued participation as an ITER partner is important to United States fusion energy research, and describe how ITER participation will inform the design of a compact fusion pilot plant as a new element of the United States magnetic fusion program. The benefits of continued U.S. participation in ITER are compelling. Planning and preparation for ITER experiments are the major focus of the U.S. fusion research program. The development of national expertise in burning plasma science requires the participation of experts and will not result from mere study of the research achievements of other nations. ITER construction is more than half complete, and the first plasma experiments are expected to begin in less than ten years. ITER is the only existing experiment with a mission to explore burning plasma physics at the power plant scale. ITER is also an ambitious research project that integrates multiple advanced technologies and combines the scientific and engineering expertise, industrial capacity, and financial resources of several nations. As an ITER partner, the United States receives full benefit from the technology that will establish the feasibility of fusion while providing only a fraction of the financial resources.

Even though ITER is recognized as “the best candidate today to demonstrate sustained burning plasma,” the committee was tasked to provide long-term guidance for the scenario in which the United States is not a partner in ITER. Because any strategy to develop magnetic fusion energy requires study of a burning plasma, a decision by the United States to withdraw from the ITER project would require a new approach to study a burning plasma and a new focus to the U.S. fusion research program. Currently, there is no mature burning plasma experiment as an alternative to ITER. The design, construction, and licensing of such an alternative to ITER would require significant development by the U.S. program. Because participation in ITER and the ITPA aids international cooperation and collaboration in fusion energy science, withdrawal from the ITER project will also require a new approach to avoid isolation from the international fusion energy research effort.

Irrespective of whether the U.S. remains an ITER partner, the committee recommends the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant at the lowest possible capital cost and the production of electricity from fusion. In this way, the committee’s long-term strategic guidance is generic and applies to both scenarios.

All previous strategic plans reviewed by the committee calls for construction and operation of a burning plasma experiment and the demonstration of scientific and technical feasibility prior to construction of a facility capable of electricity production. This committee concurs with this assessment. A burning plasma experiment is a critical next step toward the realization of fusion energy, and the science and technology gained from a burning plasma experiment, like ITER, will answer key questions needed to design a compact pilot-plant. With access to a burning plasma experiment, scientists will have the means to answer fundamental questions pertaining to energetic alpha particles created by fusion reactions, plasma transport processes in fusion reactor conditions, methods to control of plasma transients, divertor science, and the integrated scenarios that simultaneously test the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components needed for a fusion energy source.

If the United States wishes to maintain scientific and technical leadership in fusion energy development and undertake a program toward a compact pilot plant, national expertise in burning plasma science needs to be developed through hands-on operational participation and scientific study by U.S. fusion scientists.

For the scenario with the United States remaining an ITER partner, research toward the second goal of compact, attractive fusion power generation will build upon the ITER experience and focus on high power density plasmas, and the integration of core and edge physics in the regime required for a compact fusion pilot plant. Using research results from the DIII-D, NSTX-U and Alcator C-Mod programs, from advances in fusion confinement theory and simulation, a follow-on experiment as an intermediate step toward a high-pressure, compact pilot plant need not be a fusion nuclear facility, resulting in significant savings in facility cost, research access, instrumentation, and project schedule.

However, if the United States were to withdraw from ITER, the United States would need to design and construct a larger and more ambitious research facility with a capability to explore burning plasma science with deuterium-tritium operation. The direct study of high-gain burning plasma physics and access to research opportunities necessary to evaluate long plasma duration and burning plasma control methods are central long-term goals of the United States program. As an alternative to ITER, the addition of an expanded fusion nuclear program for the high-power density burning plasma facility would very be expensive for the United States to undertake without international support, and it would delay progress in the field.[57] Such an expanded fusion research program, however, would be critical for directly addressing the physics of a strongly coupled burning plasma, and addressing the key challenges discussed above.

A decision by the United States to withdraw from the ITER partnership would make international collaboration more difficult. Nevertheless, the United States would need to explore other avenues for collaboration and international cost-sharing, such as the engagement of the U.S. in the physics design for the China Fusion Energy Test Reactor (CFETR). Such international collaborations, particularly in the event of a United States withdrawal from ITER, would benefit the United States provided a vibrant national fusion program can provide value to offer to other collaborating nations.

In summary, in both scenarios, whether the U.S. remains an ITER partner, or not, the committee recommends the United States should start a national research and technology program leading to the construction of a compact pilot plant at the lowest possible capital cost. However, without ITER participation and since the long-term objective would still be the compact pilot plant, the primary initial focus of a United States program would be a high-power density research tokamak with expanded capabilities allowing study and operational experience with a burning plasma. Systems engineering and conceptual design studies for this machine, building on results from new experiments on DIII-D and NSTX-U, and state-of-the art theory and simulation, should begin as quickly as possible in response to a United States decision to withdraw from ITER in order to provide the necessary means to study burning plasma science and technology as part of a new focus to the United States fusion research program and maintain progress toward the long-term development of commercial fusion power.

SUMMARY

Major advances in both experimental and theoretical fusion science provide a strong foundation for rapid progress toward fusion development. Progress in theory and computation of fusion plasmas, coupled to well-diagnosed flexible US experiments, have increased confidence in predictions of burning plasma performance, and clarified requirements for an attractive fusion energy source. Realization of a burning plasma is essential to developing a complete understanding of the strongly coupled system, and advancing the technology needed to make fusion energy attractive.

ITER is a burning plasma experiment and the critical next step in the development of fusion energy. Methods to control plasma stability, plasma interactions with first wall materials, plasma confinement, and fusion power output will be tested. Theoretical predictions of energetic particles produced by fusion reactions and methods to sustain a burning plasma will be explored and validated. Equally important are gains in fusion engineering science and industrial capability that result from ITER fabrication and operation.

Finding: The scientific and technical benefits from the study and operation of ITER are compelling and critical to the development fusion energy for the United States.

ITER is a large and ambitious project that integrates multiple advanced technologies and combines the scientific and engineering expertise, industrial capacity, and financial resources of several nations. As an ITER partner, the United States receives full benefit from the technology that will establish the feasibility of fusion while providing only a fraction of the financial resources.

Finding: ITER plays a central role in U.S. burning plasma research activities and is currently the only existing project to create a burning plasma at the scale of a power plant. Because the ITER partnership is the central focus in the large international effort to develop fusion energy, the United States significantly benefits from participation in the ITER partnership.

Recommendation: Because the scientific and technical benefits from ITER are compelling and because ITER is the only existing project to create a burning plasma at the scale of a power plant, the Committee recommends that the United States government fulfill its commitment to construct and operate ITER as the primary experiment in the burning plasma component of its long-term strategic plan for fusion energy.

Recommendation: A near-term focus of the U.S. DOE OFES research program should maximize the scientific and technical benefits from its partnership in a burning plasma experiment.

Finding: Advances in understanding toroidal magnetic confinement, plasma control, and integrated solutions to whole-plasma optimization point to improvements beyond the ITER baseline and show how careful design and simulation can be used to lower the cost and accelerate fusion energy development.

Recommendation: In the longer-term, the U.S. DOE OFES research program should encourage the development and testing of burning plasma scenarios on ITER that contribute to reliable operation of a compact fusion pilot plant.

Finding: If the United States withdraws from the ITER project, the national research effort would be significantly disrupted, United States researchers would be isolated from the international effort, and any benefit from sharing the cost in critical burning plasma studies and fusion demonstration would be eliminated.

Finding: Without ITER, the United States would need to design, license, and construct an alternative means to gain experience creating and controlling an energy- producing burning plasma. The scale of research facilities within the United States would be more costly. The achievement of electricity production from fusion in the United States would be delayed.

Recommendation: Nevertheless, if the United States decides to withdraw from the ITER project, the U.S. DOE OFES should initiate a plan to continue research that will lead toward the construction of a compact fusion pilot plant. This should include the construction of an alternative means to study the burning plasma regime and an alternate method to engage in the international effort in the pursuit of its long-term objective for fusion demonstration.

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4

Advancing Magnetic Fusion Toward an Economical Energy Source

While construction and operation of a burning plasma experiment is a critical next step to the development of magnetic fusion energy, further research is needed to improve and fully enable the fusion power system. The interconnected science and technology for the hardware that surrounds the plasma, converts fusion power into useful heat, and breeds and recovers tritium will need to be developed for a commercial fusion power source. Additionally, research and innovations are needed to reduce the size and cost of the fusion power system and to attract industries and utilities to pursue fusion energy-based electricity production for the United States.

This chapter describes the research needed to advance magnetic fusion toward an economical energy source beyond what will be conducted with ITER. It is motivated by recent science and technology achievements that make feasible a research strategy that may shorten the time and reduce the cost required to develop commercial fusion energy. Instead of following ITER experiments with a large, and potentially costly demonstration fusion power plant (DEMO),[1] research opportunities are described for a reduced cost pathway to fusion development. Industry can now produce commercial quantities of high-temperature superconducting tapes that have the potential to be used in very high field fusion magnets that will reduce the size needed to magnetically confine a burning plasma. Advanced burning plasma operating scenarios have been investigated that may allow uninterrupted plasma confinement at high fusion power density and with very low recirculating power requirements. Emerging new technologies have been identified, like additive and advanced manufacturing and novel tritium processing technology, that may reduce the cost and improve the reliability of fusion nuclear components and systems. Taken together, these advances create a new approach to the development of commercial fusion energy, called the “compact fusion pilot plant.” The goal of a compact fusion pilot plant is to use advances in fusion science and technology to address mission elements of previous pathways to a fusion DEMO but in a facility having a small size and the lowest possible capital-cost.

This pathway to a compact fusion pilot plant merges fusion science and technology research with burning plasma studies conducted in parallel with ITER. This pathway converges in the time-frame after burning plasma demonstration in ITER (near 2040) and enables the construction of a compact pilot plant to begin near this time. When ITER operation establishes key burning plasma science and when the accompanying research program has simultaneously advanced burning plasma science, materials science, fusion nuclear science, and engineering science, the design of the compact fusion pilot plant can be finalized and construction commence. As identified in the committee’s Interim Report, without the research accompanying ITER aimed to improve and fully enable the fusion system, the United States risks being overtaken as our partners advance the science and technology required to deliver fusion energy.

Advancing magnetic fusion energy by developing a compact fusion pilot plant involves risks. A compact fusion pilot plant requires developing operation scenarios for sustaining high-power density burning plasma with the plasma exhaust capability required for compact fusion. The engineering design and fabrication of large bore, high-field superconducting magnets for fusion needs to be established. Long-lifetime materials will need to be developed and qualified for use in the compact fusion pilot plant. Tritium science and fusion breeding blanket development needs to be developed sufficiently for integrated non-nuclear testing of prototypes that can serve as the basis for blanket components that will ultimately be installed in the compact pilot plant. Finally, to be successful, a detailed system engineering effort is needed to guide a “pre-pilot-plant” research program toward construction of a low capital-cost fusion pilot plant through cost-effective research and development. The only way to retire these risks is to carry out the needed research and development.

This chapter is organized into four parts. First, previous pathways to commercial fusion are summarized, and the mission needs for commercial fusion power are listed. Second, the compact fusion pathway is presented including the research needed to establish and sustain burning plasma conditions at high power density, with low recirculating power, and using low-cost research facilities. Third, fusion nuclear science and technology is discussed followed by description of a "pre-pilot-plant" research program that will increase the technical readiness of the superconducting magnets, fusion nuclear materials, fusion nuclear components, and enabling technologies that are needed to design and fabricate a compact fusion pilot plant. Possible facilities and partnerships that further accelerate magnetic fusion energy are also described.

Finally, the committee's findings and recommendations for a national program of accompanying research and technology leading to the construction of a compact pilot-plant which produces electricity from fusion at the lowest possible capital cost. A detailed finding itemizing the technical and scientific support motivating a new national research program leading to the construction of a compact pilot plant is followed by four recommendations to resolve five critical research needs, initiate planning for the construction of new research facilities, and the adoption of a two-phase approach to its plans for the compact pilot plant so that scientific and technical risks can be addressed cost-effectively.

PREVIOUSLY STUDIED PATHWAYS TO COMMERCIAL FUSION ENERGY

The long-term objective of previous pathways to commercial fusion energy is the design and operation of a demonstration fusion power plant (DEMO). A DEMO would produce electricity, operate routinely and eliminate all technical barriers to the commercialization of fusion power. Previous designs for a fusion DEMO are for large, high-power facilities that build upon the ITER design with technologies needed to produce net electricity from fusion for long periods of time.

Two approaches have been proposed to reduce technical risks of a DEMO facility and to satisfy fusion nuclear licensing requirements. One approach builds an intermediate facility, called a fusion nuclear science facility (FNSF), prior to DEMO. An FNSF would establish the materials and component database in the real fusion in-service environment before proceeding to a larger DEMO facility. The other approach would design and build a large DEMO facility with a "slow start" where necessary fusion nuclear components would be installed over time in a staged approach.

Figure 4.1 illustrates the timelines for various pathways to DEMO and to a commercial fusion power plant developed for Korea, Europe, Japan, and China and previously considered for the United States. All pathways have the same goal of operating a DEMO near 2050. The United States has not adopted an official strategy toward a DEMO, but the U.S. DOE FESAC has recommended research leading to the construction of an FNSF prior to DEMO.[2,3] The FNSF would be the first part of a two-step approach to a fusion power plant that would commence in parallel with the study of burning plasma in ITER. The second step is a DEMO device. Variations of the FNSF differ in size and capability, but the strategic argument for the FSNF is to understand the behaviors of materials and fusion components prior to the pursuit of electricity production in the larger DEMO device. Several options for an FNSF have been considered in the United States depending how closely the FNSF approaches the characteristics of a power-producing fusion energy device and that vary the shape of the magnets that confine the toroidal burning plasma.[4]

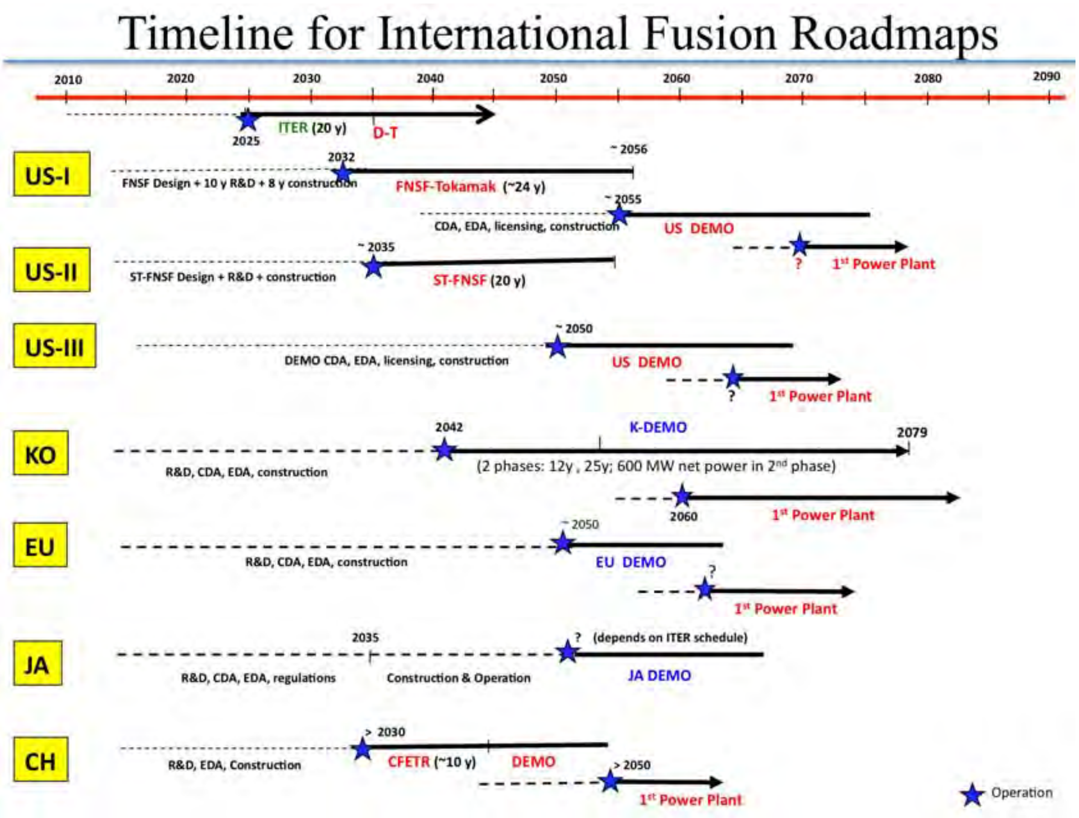

FIGURE 4.1 Timelines for the pathways to the first commercial power plant for the United States, Korea, Europe, Japan, and China. All pathways have the same goal of operating a DEMO near 2050. The fusion energy pathway for the United States is not determined, and proposals have been made to construct an intermediate FNSF prior to DEMO. The Korean and Chinese DEMO would be designed and operated in two phases. For Japan and Europe, construction of DEMO would begin near the end of ITER operation. SOURCE: Laila El-Guebaly, "Worldwide Timelines for Fusion Energy," presented to the committee (November 2017).

The pathways considered by Korea and China proceed directly from ITER to DEMO, but the Korean and Chinese DEMO facilities would be designed and operated in two phases. Higher-power and longer-duration fusion power would occur in the second phase after the first-phase established burning plasma operating scenarios and some fusion nuclear technologies. For Japan and Europe, construction of DEMO would begin near the end of ITER operation in order to start DEMO operation at the earliest possible date.[5] The EU fusion roadmap Horizon 2020[6] requires the EU-DEMO to be based on mature technologies and use reliable regimes of operation extrapolated from the ITER facility. All of the pathways listed in Figure 4.1 include a DEMO device built at a size and power level larger than ITER.

The various international pathways to commercial fusion energy address equivalent technical research and development needs. In the United States, these research needs were most recently described in the 2007 FESAC committee on Priorities, Gaps, and Opportunities[7] and the 2009 report of U.S. DOE Office of Science Research Needs Workshop for Magnetic Fusion Sciences.[8] Scientific and technical questions were organized into three broad themes defined in terms of the knowledge required prior to DEMO. These were:

- Creating predictable high-performance steady-state plasmas sufficient to create and sustain a burning plasma meeting all of the conditions required for practical production of fusion energy.
- Taming the plasma-material interface sufficiently to design and build robust material components that interface the hot plasma in the presence of energetic fusion neutrons.
- Harnessing fusion power sufficiently to design and build reliable systems that convert fusion energy to useful forms of energy and breed a self-sufficient supply of tritium fuel.

These reports recommended an integrated program of research to address all of the scientific challenges of fusion energy including fusion engineering, materials science, and plasma physics.

As presented in Chapters 2 and 3, the world-wide focus on the construction and preparation for burning plasma experiments on ITER has resulted in significant progress in the first theme to create predictable high-performance steady-state plasmas sufficient to create and sustain a burning plasma. Important progress has also been made toward the second theme of plasma-materials interaction needed to design and predict performance of the ITER divertor. Progress in the third research theme, the technical readiness to harness fusion power, is least well-developed. In a future nuclear fusion power facility, virtually every major component will require novel materials compatible with fusion's energetic neutron production. Additionally, fusion nuclear components will need to safely and efficiently fuel, exhaust, breed, confine, extract, and separate unprecedented quantities of tritium.[9]

The development path and technical missions to progress beyond ITER toward a commercial fusion power plant were recently summarized based on a detailed system engineering study for an FNSF. In addition to the study of burning plasma and control, the development of fusion technology is categorized into three steps. Fusion-relevant neutron exposure of materials and non-nuclear testing of fusion components are tests that can be prepared in the short term. The purpose of the second step, the FNSF, is to produce environments similar to a fusion power plant for evaluating heat removal and the impact of energetic fusion neutrons. Integration of those systems related to electricity production, including high efficiency heating, current-drive, thermal management, breeding, and gas processing, are deferred to the last step, the large DEMO device.

For all of these development pathways, the long-term objective is the design and operation of a demonstration fusion power plant (DEMO). The pathways are distinguished by the number and size of research facilities needed to achieve the integrated technical efficiency to produce electricity from fusion energy.

A COMPACT AND LOWER-COST PATHWAY TO FUSION ELECTRICITY

New technologies, such as high-temperature superconducting magnets and advanced materials, and new achievements in burning plasma science now make smaller, less-costly research devices possible and fusion research and development more affordable and attractive. This has two strategic implications:

- In place of a single-step approach to a large fusion demonstration facility (DEMO), the opportunity exists today to start the interconnected science and technology research leading to construction of a compact pilot plant and, ultimately, the production of electricity with a device with significantly lower cost.

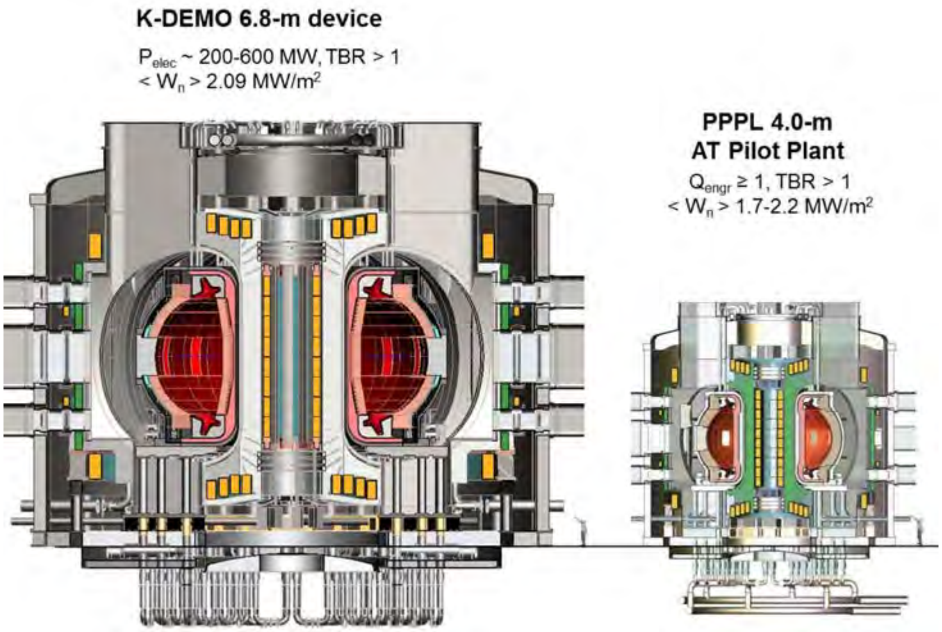

FIGURE 4.2 Illustration of the DEMO approach and the pilot plant approach to next-step fusion energy development devices. On the left is a design of the K-DEMO capable of producing as much as 600 MW of electricity. On the right is a diagram of a smaller and less-costly pilot plant. While not producing as much electricity, a compact pilot plant would allow low-cost testing and development of the science and technology for commercial fusion power. SOURCE: T. Brown, “U.S. Next Step Strategy for Magnetic Fusion,” submitted to the U.S. Workshop on Strategy for Magnetic Fusion, Madison, WI, July 2017.

- In place of two-step approach with a fusion nuclear science facility (FSNF) having a mission limited to fusion component development followed by a second DEMO facility, recent science and technology advances suggest a compact fusion pilot plant might be built at a cost comparable to previous FNSF designs while being ultimately capable of demonstrating the overall systems efficiency required to produce electricity.

Relative to previous pathways to commercial fusion energy, a compact fusion pathway targets smaller device size, lower capital cost, and shorter development steps. A research approach that minimizes the capital cost of major research facilities is a less costly pathway to the demonstration of fusion electricity. A research approach that includes the production of electricity as an objective motivates, from the beginning, efforts to optimize overall systems efficiency as an essential part of the evaluation of the compact fusion pilot plant.

This compact fusion pilot plant would be a pre-commercial research facility with a burning plasma at its core and surrounded by a blanket to capture fusion heat and neutrons. In addition to the production of fusion electricity, the pilot plant would ultimately be capable of uninterrupted operation for weeks and produce tritium, the heavy isotope of hydrogen in fusion fuel, from lithium-containing blankets that surround the plasma. As a pilot plant, its purpose will be learning, but the knowledge obtained would be sufficient for the design of the first commercial fusion power systems..

The pilot plant pathway to commercial power has been examined favorably by several studies for many years.[10] Figure 4.2 compares one DEMO design to an example of a pilot plant designed with superconducting magnets, B = 6T, small size, R = 4m, and relatively low fusion power, 500 MW.[11] By comparison, the K-DEMO (R = 6.8m, B = 7.4T) design would be much larger and costlier but produce 2000 MW of fusion power.[12] Besides decreasing the cost of fusion research facilities, a smaller, compact fusion pilot plant addresses market trends from United States electrical utilities seeking lower capital-cost capacity additions, shorter construction times, and more flexible siting options that result from smaller power-plant footprint.[13]

Another advantage of a compact approach is that it reduces the financial risk in combing two fusion research missions in a single device, provided that sufficient progress is made to retire technology risks. The initial pilot plant operation would demonstrate net-electric equivalent performance in a compact fusion system, focusing on integrated core/edge performance, assessing plasma material interactions, demonstrating tritium pumping, limited breeding, safe handling and extraction. This initial phase would not include long-pulse fusion power production and would not demonstrate self-sufficient tritium production. The second phase of the pilot plant would seek near continuous operation, allow for materials/component testing with neutron fluences approaching power-plant levels, and provide integrated blanket testing. Upon success of this second phase, the compact fusion pilot plant studies would have reduced both the economic and technical risks for fusion energy-based electricity production and will motivate further involvement from industries and utilities in the United States.

The scientific and technical opportunities for developing a compact fusion pilot plant are described below. The important relationship between compact size and high magnetic field is discussed along with the engineering challenges associated with high-temperature superconducting magnets and the plasma science and materials science challenges associated with continuous operation and high-power plasma exhaust. Fusion nuclear science and technology, opportunities for new research facilities, and opportunities for expanded international collaboration are also discussed further.

High-Magnetic Field Strength for Compact Fusion

The relationship between high magnetic field and compact fusion confinement has been appreciated for decades.[14,15] Fusion power density is proportional to the square of the plasma pressure, $0.08\ P^2$ (MW m^{-3}), where P is the plasma pressure in atmospheres. Because the maximum achievable plasma pressure increases in proportion to the magnetic pressure, fusion power density increases rapidly with increasing magnetic field, in proportion to B^4. Furthermore, the confinement time in a magnetized plasma scales with the number of gyro-radii across the plasma. At fusion temperatures, this number scales with the product of the plasma size and the magnetic field, $R \times B$. Thus, if the magnetic field doubles, the fusion power density can increase as much as 16-fold while maintaining the same fusion power gain at half the size.

The magnet technology with the highest possible magnetic field generally determines the size of magnetic fusion devices. A smaller compact fusion power source becomes possible with the availability of higher field magnets provided the compatible plasma components can be developed to control, sustain, and utilize the high-power density burning plasma.

Early compact magnetic fusion experiments were built with copper magnets, where high magnetic field strength could be reached for short pulses using novel engineering to deal with very large magnetic forces. The world's record for volume-averaged plasma pressure was set in September 2016 in the Alcator C-Mod device at the Massachusetts Institute of Technology, which operated at high magnetic field and physics-based optimization. (See Figure 2.3.) Two of the three burning plasma experiments discussed in the 2004 NAS Burning Plasma Assessment were designed with copper coils in order to reach burning plasma conditions during short pulses in devices that would be smaller, but less capable, than ITER.

Copper coils require large currents and consume large power when operating at high magnetic field. For this reason, continuous high-field operation for fusion is not possible with copper coils. All power producing magnetic fusion concepts considered today require superconducting magnets to reduce recirculating power and significantly improve the efficiency and economics of electricity production.[16] At the time ITER was designed, the highest-field superconductor available was niobium-tin (Nb_3Sn). To reach burning plasma conditions, the ITER superconducting magnets are the largest ever built, with a

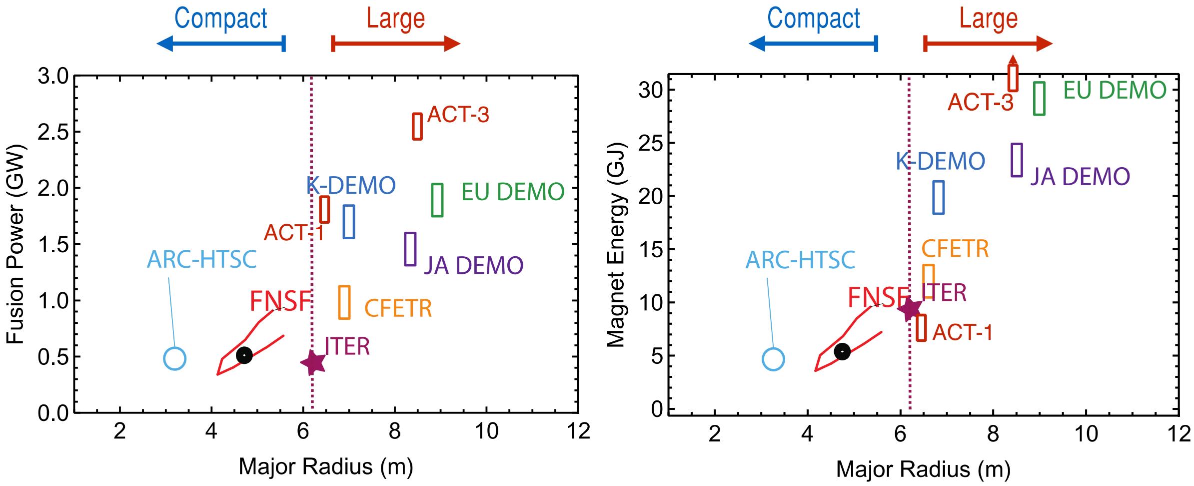

FIGURE 4.3 Diagrams of (a) fusion power and (b) magnet energy (within plasma volume) versus plasma major radius for several next-step burning plasma devices including proposed DEMO reactors. Compact devices are smaller and require superconducting magnet systems with lower magnet energy requirements. DEMO devices proposed in China (CFETR), Korea (K-DEMO), Japan (JA-DEMO) and Europe (EU-DEMO) are larger than ITER and require higher energy superconducting magnets. The ARC device, proposed by MIT, and the Fusion Nuclear Science Facility (FNSF), developed in the United States, are compact next-step devices with lower cost. SOURCE: Adapted from "Producing Electricity in a Fusion Nuclear Science Facility or Similar," C. E. Kessel, paper submitted to the committee, April 2018 and C.E. Kessel, et al., "The Fusion Nuclear Science Facility, the Critical Step in the Pathway to Fusion Energy," Fusion Sci Technol 68, 225 (2017).

total magnetic stored energy of 51 GJ, a nominal mechanical stress of 600 MPa, and a magnetic field strength of $B = 5.3$ T within the plasma.[17] Today's opportunity for compact magnet fusion energy results from the potential for high-field superconducting magnets. New high-temperature superconductors may make possible fusion magnets that can achieve fusion gain and power equivalent to ITER but at a significantly lower size and cost.

Figure 4.3 illustrates the sizes for several proposed superconducting next-step burning plasma devices at $A \sim 3$, including ITER. Various DEMO designs have magnetic fields comparable to ITER and achieve higher power at larger size. The large EU-DEMO device ($R = 9$ m) requires a system of superconducting magnets having a magnet energy about four times larger than ITER. In contrast, recent FNSF conceptual designs[18] (which are not designed to achieve the same power gain as ITER) and the proposed ARC device[19] are much smaller fusion devices that operate with higher magnetic field strength but smaller stored magnetic field energy than in ITER.

Two engineering challenges will need to be addressed to increase the magnetic field in a compact fusion device. The first challenge is the development of superconductors with higher critical current density and higher critical magnetic field strengths. With the new commercial availability of rare-earth barium copper oxide superconducting materials deposited on steel tapes, the prospects for meeting this challenge appear good. The second challenge is the mechanical design of the high field tokamak. At high magnetic fields, the magnetic force becomes extremely large. Within larger devices, like ITER, the central force of each toroidal field magnet is supported by wedges between adjacent coils and includes a large ohmic heating solenoid. The CFETR,[20] EU-DEMO,[21] K-DEMO,[22] and J-DEMO[23] designs listed in Figure 4.3 are examples. By comparison, with a compact fusion device, innovative mechanical configurations are needed to support the large forces on the superconducting magnets. The magnetic field strength used for conceptual design studies of compact fusion devices are limited by the high stresses within the materials needed to support the magnets.[24] However, the FESAC Report on *Transformative Enabling Capabilities* concluded (p. 28) a "consensus within the magnet community that existing high strength stainless steel and superalloy materials are adequate for projected fusion requirements." Additionally, smaller and higher-field designs incorporate multiple load paths, called bucked and wedged, to support the magnet forces.[25]

In a fusion device built using superconductors, the field from the toroidal magnets does not change in time. However, the poloidal field magnets that are used to start-up the burning plasma and control its position and shape will need to change in time. The development of high-field superconductors for the poloidal field coils require the solution of challenging technical issues related to time-varying magnet currents. These engineering issues will influence the magnet configuration, aspect ratio, and location of poloidal field magnets within the device.

While new high-temperature superconductors require engineering developments to reach the high magnetic field strength for compact fusion, they may provide additional benefits as compared to low-critical temperature superconductors. For example, demountable toroidal field magnets may allow simplified maintenance, as proposed in the ARC compact fusion device.[26] Because the new superconductor is deposited in thin layers on flexible steel tapes, magnet winding and manufacturing may be superior than the wind-and-react method required for Nb_3Sn. Low aspect ratio compact design has been proposed both in the United States[27] and by Japanese scientists.[28,29] In each case, size reduction resulting from high-field compact tokamak reactors is significant when compared with conventional reactor designs. Further mechanical design is required to assure adequate structural integrity and compatibility with high fusion power density, a compact tritium breeding blanket, effective neutron and gamma shielding, and non-inductive operation.

> **Finding:** Although additional research, including magnet engineering research, is needed to demonstrate the viability of the compact pathway to fusion power, the combination of new high-field superconducting magnet technology with advanced burning plasma science is a significant opportunity to decrease the size and cost of a magnetic fusion power system.

Plasma Power Handing for Compact Fusion

Power handling is one of the crucial challenges for magnetic confinement fusion, and the compact pathway to economical fusion path may either heighten or help to mitigate this challenge.

The escaping plasma exhaust that contacts the divertor will need to be configured to avoid unacceptable thermal damage or erosion of plasma facing components due to sputtering. Compared with present-day devices, the escaping plasma heat flux will increase in commercial fusion power devices and require design improvements to properly cool the divertor and first-wall and allow continuous uninterrupted operation. Additionally, plasma relaxation phenomena, called edge-localized modes (ELMs) driven by instabilities localized to the plasma edge region,[30] should be controlled or prevented in order to avoid first-wall material damage.

Variations of the divertor approach taken for ITER may also prove applicable for the compact fusion pilot plant. The divertor is constructed from water cooled blocks with plasma-facing tungsten armor. The very high heat flux from the plasma is prevented from direct contact with the divertor armor by volumetric radiation and recombination, called a "detachment." Uncertainties exist how divertor detachment can be achieved in next-step fusion devices, and the results from ITER experiments will provide crucial measurements with which to test predictive models. Nevertheless, the power flow of the escaping plasma exhaust is observed to be narrow, with a width inversely proportional to the poloidal magnetic field, $B_p \approx B/Aq$, where A is the plasma aspect ratio and q is the plasma safety factor (inversely proportional to the helical twist of the magnetic field lines.) A fusion device with the same peak power flux to the divertor as expected in ITER will require that the thermal power escaping the plasma surface scale in proportion to RqA/B and likely also require seeding with impurity atoms (like argon, neon, or other radiating atoms) that scale in proportion to qA/B.[31] Self-consistent models for detached divertors indicate the impurity fraction required for detachment scales in proportion to the ratio of the escaping

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FIGURE 4.4 Illustration of magnetic fusion operation as a function of the magnetic field strength, *B*, and toroidal major radius, *R*. Three diagrams are shown with different assumptions of the confinement factor, *H*, the normalized plasma pressure, β_N, and plasma safety factor, *q*. The fusion power increases rapidly with both size and magnetic field, $\propto R^3B^4$; the plasma current increases linearly, $\propto RB/q$; and the power flux to the divertor is assumed to scale as the product of the plasma thermal power and (B/Rq). As the size of the fusion power source decreases (*panel a*), the magnetic field must increase. As the size of the fusion power source increases (*panel c*), the fusion power output increases. Finally, when both the plasma pressure, β_N, and safety factor, *q*, are sufficiently large, about $q\times \beta_N > 25$, the plasma current is self-sustaining without external current drive power, as shown in (*panel a*). SOURCE: Adapted from H. Zohm et al, "A stepladder approach to a tokamak fusion power plant," 2017 Nucl. Fusion 57 086002.

fusion power to the poloidal magnetic field. For this reason, a compact pilot plant operating at lower power but higher magnetic field may be preferred to a higher-power fusion system because the compact design allows lower impurity concentration within the detached divertor region.

As the magnetic field increases, the fusion device becomes more compact and produces less total power at equivalent gain. Figure 4.4 illustrates these trends which show how the limits imposed by the divertor heat flux and fusion power change as the magnetic field, *B*, and the device size, *R*, change while keeping the aspect ratio at $A \sim 3$. Because the exhaustible heat is proportional to the plasma surface area while the device cost is proportional to the magnetic energy within the plasma volume, a compact fusion approach can be a cost-effective approach for magnetic confinement fusion from the power handling point of view as well as by reducing total capital investment for a power plant.

Another challenge is controlling the transient heat flux due to ELMs (Edge Localized Modes). ELMs are edge relaxation phenomena believed to be driven by the peeling/ballooning mode.[32] Several methods have been demonstrated to suppress ELMs, including the application of 3D magnetic perturbations in DIII-D[33] and steady operation without any transient ELM events. These include the quiescent "QH-mode"[34][35] associated with edge harmonic oscillation (EHO) to enhance edge transport, "I-mode"[36] associated with the weakly coherent mode (WCM), and improved energy confinement with reduced particle confinement. Eliminating or reducing the transient heat flux due to ELMs significantly lengthens the lifetime of the divertor armor. Because of the higher magnetic field of a compact fusion reactor, operation can occur at reduced plasma current and higher *q*, which has been found to assist in ELM-free operating modes.

Finally, ongoing research, discussed in Chapter 2, is now evaluating promising advanced divertor configurations such as the Snowflake divertor,[37] Super-X-divertor,[38] and Small-Angle Slot (SAS) divertor.[39] A recent low aspect ratio HTS FNSF/Pilot plant design by Menard[40] successfully showed that the long-leg and Super-X-divertor can be implemented for the outboard divertor leg in a compact fusion system. The SAS divertor, first tested in DIII-D, is a compact divertor geometry in which stable detachment has been obtained experimentally, showing that a slot with a V-shaped corner is very promising for a compact fusion power source.

> **Finding:** While methods to remove heat from the divertor and reduce material erosion due to plasma sputtering remain active research areas, current understanding of divertor scaling indicates that the compact fusion pathway at higher field and lower total power may benefit power handling solutions for fusion energy.

Achieving Steady Uninterrupted Operation for Compact Fusion

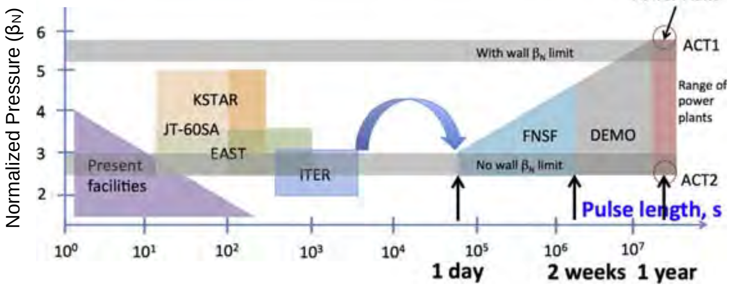
A commercial fusion power source will need to produce electricity continuously for several months at a time. A critical goal for a compact fusion pilot plant is to demonstrate uninterrupted operation and to establish the basic science and technology needed for commercial fusion power.

Figure 4.5 shows diagrams of fusion plasma performance and plasma pulse duration. The fusion energy gain is roughly proportional to the fusion "triple product," $n(0)\times\tau_E\times T_i(0)$ equal to the product of the central plasma density, the characteristic time for energy loss, and the central temperature of the fusion fuel. The fusion gain and triple product generally increase quickly with the size and magnetic field strength of the fusion containment device, $n(0)\times\tau_E\times T_i(0) \propto (R\,B)^3$ at fusion temperatures and densities. The highest fusion performance has so far been achieved using large copper magnets (e.g., the JT-60U, JET, and TFTR experiments). In these devices, long-pulse operation requires reduced toroidal magnetic field, resulting in reduced plasma performance. Studies of long duration plasma confinement has become possible with superconducting magnets such as the Tore Supra (TS) ,[41] EAST, and K-STAR experiments. The longest plasma duration was achieved in TRIAM-1M,[42] but TRIAM-1M could not simultaneously achieve high fusion performance due to its small size, $R = 0.84$ m. Two superconducting stellarators, the W-7X ($R = 5.5$ m, $B = 2.4$T) and LHD device ($R = 3.9$ m, $B = 3.0$T), have, respectively, two and three times higher energy superconducting magnet systems than in the EAST tokamak, and they are sufficiently large to allow study of fusion performance at pulse lengths comparable to the superconducting tokamaks. As shown in Figure 4.4, the technical achievement of high fusion gain and long plasma duration will be tested for more than one minute in the JT-60SA device,[43] expected to be commissioned in 2010 in Japan, and for several minutes in ITER and additional facilities, like FNSF, have been proposed to extend fusion pulse lengths from days to weeks.

To achieve efficient steady-state operation, most of the plasma current will need to be self-generated instead of driven by injection of particles or electromagnetic waves. Indeed, the plasma current in high-gain fusion experiments have been driven by magnetic induction, and the plasma current in the highest performance experiments in ITER also results from induction.

Self-generated current is called "bootstrap current," and the fraction of plasma current sustained by the bootstrap effect scales in proportion to the plasma poloidal beta, β_p, where the plasma poloidal beta measures the ratio of the plasma energy to the magnetic energy of the plasma current. The poloidal beta is proportional to the normalized plasma beta and the plasma safety factor, $\beta_p \approx 0.03\, q\, A\, \beta_N$. The high poloidal beta regime occurs when $q\,\beta_N \sim 25$ (when the plasma aspect ratio is near 3) and the self-generated bootstrap current fraction, f_{BS}, reaches 100%. This mode of operation is called the advanced tokamak operation.[44] JT-60U[45] sustained high bootstrap current fraction (~75%) discharges for 7.4 s; TCV achieved 100% bootstrap current; and DIII-D[46] achieved a fully non-inductive high bootstrap current fraction (~ 60%) operation around $\beta_N = 3.5$, which is twice the normalized pressure in the ITER reference scenario. These high poloidal beta regimes also have improved energy confinement, making high poloidal beta regimes promising modes to operate a commercial fusion power device and a fusion DEMO. Higher magnetic field in the compact fusion pathway allows higher fusion power density while also operating with high poloidal beta and lower plasma current. As shown in Figure 4.4(a), a compact fusion pilot plant (shown as the star symbol and labeled "HT-SC Compact") operating at high magnetic field and within an advanced fusion confinement regime would produce significant fusion power while

(a) Normalized Plasma Pressure vs. Plasma Duration



(b) Fusion Triple Product vs. Plasma Duration

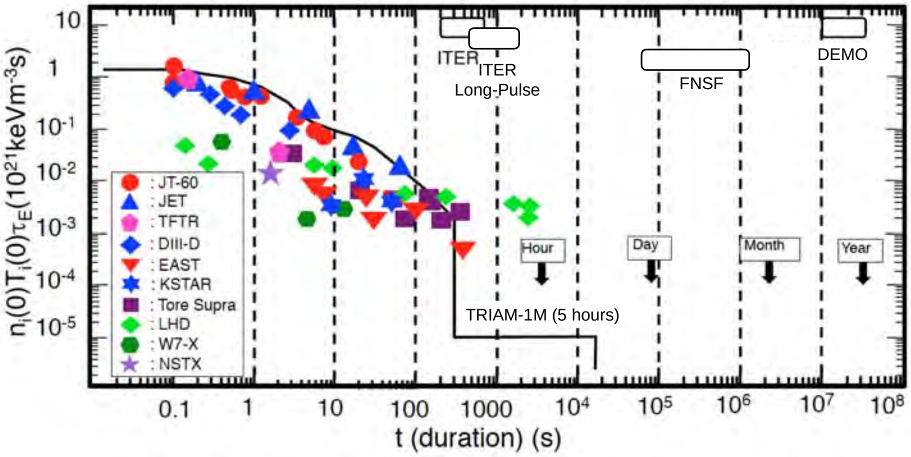


FIGURE 4.5 Diagrams of fusion plasma performance versus duration of plasma operation. Top (a) shows normalized plasma pressure versus duration, with high β_N indicative of high-power density and self-sustained plasma current. Bottom (b) shows the fusion triple product versus duration, with the product $n_i(0)\,\tau_E T_i(0)$ proportional to fusion energy gain. The highest performance is achieved for short duration. The longest plasma duration is achieved with superconducting magnets with sustained injection of external plasma heating power. TRIAM-1M (Japan) has world record in plasma sustainment of 5 h and 16 min. Tore Supra (France) was sustained for more than 5 min, and the plasma was sustained in the superconducting Large Helical Device (LHD) in Japan for 48 min. SOURCE: Adapted from M. Kikuchi, M. Azumi, *Frontier in Fusion Research II* (Springer, 2015) and from C.E. Kessel, et al., "Overview of the fusion nuclear science facility, a credible break-in step on the path to fusion energy," *Fusion Eng. Des.* (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.05.081.

operating at lower plasma current and full bootstrap current. Similar levels of fusion power were described by the HTS-ST pilot plant design developed by Menard and co-authors.[47]

As was described in the Chapter 3 section on "Extending ITER Performance," just as recent advances in theory and simulation provide opportunities to significantly extend ITER performance, these advances also improve the prospects for a compact fusion pilot plant. Experiments at U.S. research facilities have achieved record plasma pressure, demonstrated advanced operating scenarios, like the Super H-Mode, and tested methods to improve divertor power handling. Simulations of integrated core-pedestal performance have already been used to optimize steady-state scenarios on DIII-D and make initial predictions for ITER. These advances optimizing fusion performance for ITER combine with advances in magnet technology to motivate the reduced size and capital cost of the compact fusion pilot plant.

> **Finding:** While significant progress is needed to achieve uninterrupted operation of a high-performance fusion confinement device, the higher magnetic field in the compact fusion pathway,

when combined with advanced operating scenarios, appears to allow operation at high fusion power density, high poloidal beta, and high bootstrap current fraction more easily than other pathways to commercial fusion power.

THE TECHNOLOGY PATHWAY TO ECONOMICAL FUSION POWER

Research aimed at developing a fusion-based power plant has, to date, focused mainly on the plasma physics and confinement itself, including the plasma, the divertor and first wall, as well as the magnets and heating systems. These are all necessary features of a power plant, and significant progress has culminated with the construction of ITER. But, these aspects alone are not sufficient for a fusion energy pilot plant. The attractiveness of a fusion system, in terms of economics as well as safety and environmental considerations, is mainly determined by the materials and design of systems that will extract the fusion power in order to convert it to electricity and sustainably generate, or breed, tritium. At present, these systems for the divertor and first wall, and integrated blanket are at a very low technical readiness level, and significant fusion nuclear science and technology research is needed to provide the technological foundation required for the design and construction of a compact fusion pilot plant.

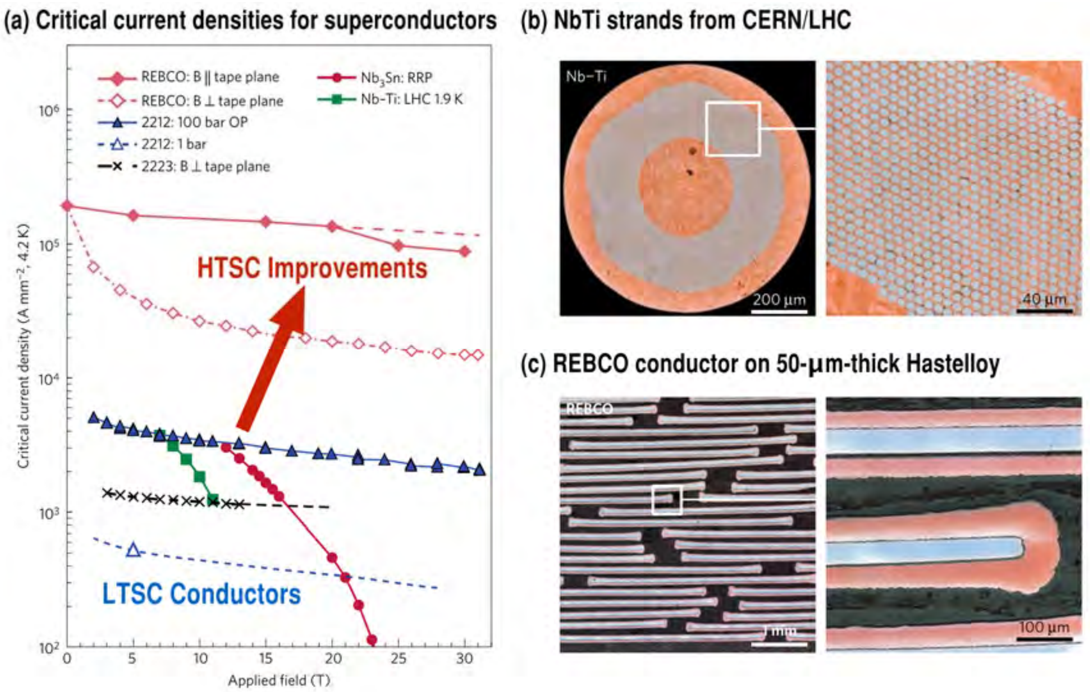
As noted earlier, a number of transformative enabling capabilities illustrate how rapidly developing technology advances may speed progress and lower the cost of fusion energy development. These transformative capabilities include advanced materials, high temperature and/or high field magnets, and tritium processing, all of which offer the potential to significantly increase the technical readiness level to enable construction and mitigate risks toward the initial operation of the compact, advanced fusion energy test facility. In particular, the TEC report of the U.S. DOE/FESAC on Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy noted that “magnet systems are the ultimate enabling technology for magnetic confinement fusion devices. Advances in the development of superconductors that operate at higher temperature and higher field, referred to as HTS, present a potentially transformative opportunity to significantly enhance the performance and feasibility of a large variety of magnetic confinement devices.”

In addition to advancement in superconducting magnet technology, the TEC report described recent advances in “novel synthesis, manufacturing and materials design are providing the most promising transformation enabling technologies in PMI and nuclear fusion materials to enable fusion energy for the future.” The TEC report identified a number of potentially transformative developments in tritium extraction and processing that show promise for a commercial fusion reactor, but will require further research and development, in addition to demonstration in a compact fusion energy test facility.

In the following, opportunities to advance magnetic fusion energy through engineering science, materials science, and fusion nuclear technology are described. Taking advantage of these research opportunities would increase the technical readiness needed for the design and construction of a compact fusion pilot plant.

High-Critical-Temperature Superconducting Magnets

Magnetic fusion energy requires access to the highest possible magnetic fields that can be maintained with superconducting magnets. In general, the highest magnetic fields achievable in practical large-bore superconducting magnets have been limited by the properties of the superconducting materials themselves. The two main well-established options are low-critical-temperature superconductors (LTS). Niobium-titanium (NbTi) is used in Tore-Supra, EAST, K-STAR, and the two superconducting stellarators. The higher-field niobium-tin (Nb_3Sn) superconductor is used for ITER. Since the mid-2000s, a new class of high temperature superconducting (HTS) materials was successfully used for large-scale applications: rare-earth Barium Copper-Oxides (REBCO) tapes and Bi-2212 round strands. Figure 4.6 shows a plot of the critical current density versus magnetic field for low temperature superconducting (LTC) and HTS magnets. REBCO has performance anisotropy parallel and perpendicular to the magnetic


(a) Critical current densities for superconductors

(b) NbTi strands from CERN/LHC

(c) REBCO conductor on 50-µm-thick Hastelloy

FIGURE 4.6 Critical current density as a function of applied magnetic field (a) showing the achievements of new HTS concepts. From Larbalestier, et al., Nature Materials 13, 375 (2014). Also shown are cross-sections of low-temperature superconducting strands from CERN/LHC and high-temperature conductor grown on strong Hastelloy substrate.

field but has high critical current density at high field. Bismuth strontium calcium copper oxide (BSCCO) superconductor, such as Bi 2212 and Bi 2223, has lower current density at high field but each has its own merit compared to REBCO. Today, REBCO tapes are commercially available from at least seven manufacturers (AMSC, Fujikura, Shanghai Superconductor, SuNAM, SuperOx, SuperPower, and SWCC Showa).[48]

REBCO superconductors offer the potential to carry sufficient current density for magnet applications at fields up to 100 T.[49] REBCO has been successfully used to reach fields over 40 T in solenoids[50] and has demonstrated engineering current densities exceeding 10 A/mm^2.[51] This is an order-of-magnitude higher current density compared to conventional low temperature superconductor fusion magnets, and has generated considerable interest from the private sector. Indeed, the recent MIT – Commonwealth Fusion Systems collaboration has announced it is moving forward with plans to design, construct and test a large-bore magnet using HTS that is central to the SPARC design of a compact fusion device with a peak field of 23 T.[52]

At present, HTS magnets have not been tested in the configuration or at the scale needed for fusion experiments. Key challenges include magnet quench detection and protection, conductor stress/strain management and characterization of radiation resistance. There is consensus within the magnet community that existing high-strength stainless steel and super-alloy materials are adequate for projected fusion requirements. Although REBCO is extremely stable in operation, quench detection is a significant issue due to very slow propagation of the normal zone. The status and future directions of high magnetic field science, including the potential for fusion energy applications, were assessed in 2013.[53] Important goals of the Magnet Development Program of the U.S. DOE Office of High Energy Physics are to investigate fundamental aspects of magnet design that lead to substantial performance improvements and cost reduction.[54] Progress in the use of HTS magnets for fusion energy applications have been reported; however, additional engineering research is needed to gain full-size operating experience with fusion magnets, including magnet quench detection and protection, demountable coil development and testing, conductor stress/strain management, and characterization of radiation resistance.

> **Finding:** While additional research and development is needed to establish the technical basis for large high-field HTS magnets, the growing industrial capability to produce HTS conductor, opportunities to partner with industry and other U.S. DOE program offices, and the rapid progress in HTS magnets may enable significant reductions in the size of magnetic fusion devices and support the compact lower-cost pathway to fusion development.

Advanced Materials and Manufacturing Methods

Overcoming the performance challenges of materials and structures in the fusion energy environment is a daunting challenge but yet is critically important to realize the promise of fusion as a practical energy source. Development of materials, components and structures for any complex engineered system generally occurs in a series of steps, proceeding from relatively simple single variable experiments to very complex, fully integrated multiple variable tests. Commercially available additive manufacturing tools exist today and the FESAC Report on *Transformative Enabling Capabilities* (pp. 35-36) noted the rapid advancement of capabilities including mixed material printing, multi-scale features, and large component manufacture.

The first step on the development path begins with screening experiments that are performed under carefully controlled laboratory conditions. These experiments establish the basic mechanical and physical properties, chemical compatibility, and fabrication and joining technologies of candidate materials. If satisfactory results are obtained, more complex experiments are performed in order to identify materials that perform well in partially integrated or multiple variable tests. The final stage of material development involves fully integrated experiments with prototypical test sections that are carried out in an environment combining the appropriate nuclear, chemical, thermomechanical and magnetic fields necessary to establish lifetime and performance limits. The ultimate goal is to develop an extensive material database that includes chemical and mechanical properties, and physics based models to describe the material performance within a fusion power system.

Fortunately, as noted previously in this Chapter, significant advances in materials synthesis, manufacturing and materials design provide promising transformative capability to develop the integrated divertor, first wall and blanket materials to survive the fusion environment. Advanced manufacturing offers the potential to locally tailor the material microstructure within a single component by varying the manufacturing process parameters, and to create complex structures that were simply not possible with conventional methods. Further, advanced manufacturing will lead to complex lattice or composite structures for lightweight yet strong components that could optimize cooling channels to increase heat removal capability. While these tailored materials and complex structures require testing in the neutron and high heat flux environments to characterize their properties for optimizing the material microstructure and component design, advanced manufacturing offers substantial opportunities to develop complex hierarchical composites and self-healing materials to enable breakthroughs in emergent fusion materials.

Complex composites and complex solid phase alloys also have promise to demonstrate radiation tolerance, or even radiation resistance that could be transformative for fusion divertor, first wall and blanket materials. This use of complex composite geometries may significantly improve the performance of refractory materials for fusion energy applications, and recent developments in continuous fiber and laminate composites demonstrate promising thermal fatigue and thermo-mechanical response in laboratory experiments.[55] As well, advanced manufacturing techniques could lead to the development of hybrid material systems that encompass the self-healing and renewable characteristics of liquid metals with a solid-state matrix that could provide a beneficial plasma facing component with optimal heat removal. Furthermore, significant developments in SiC/SiC composites have been demonstrated in the ceramic gas turbine industry, and have transformative potential for nuclear fusion pilot plant components.

The FESAC Report on *Transformative Enabling Capabilities* also called attention to novel tritium extraction technologies proposed for liquid metal breeding blankets and for plasma facing components. Tritium science, extraction technologies, and fuel processing are critical challenges for fusion energy systems, and significant challenges will need to be overcome including the need to develop effective tritium permeation barriers to prevent release of sizable quantifies of tritium.[56]

> **Finding:** While advanced manufacturing and complex material component design have transformative potential, research is required to move beyond the early stage of developing these alloys and composites. This includes radiation effects, chemical compatibility and corrosion, unknown response to plasma material interactions and tritium permeation, and component performance and degradation in the complex neutron, plasma material and thermal-mechanical loading conditions. Studies will need to proceed from relatively simple single-variable experiments to very complex, fully integrated, multiple variable tests.

Enabling Technologies for Heating, Measurement, Plasma Control, and Safe Maintenance

Continued development of the technologies used to heat, control, and measure burning plasma will be needed as the level of fusion power increases and the duration time of the plasma approaches steady-state conditions. Additionally, engineering strategies need to be developed for subsystem and component reliability and efficient remote maintenance of fusion nuclear components.

Development of a compact fusion pilot plant with higher magnetic field strength will require development of a new generation of higher frequency sources for radio waves and millimeter waves and also technology research to extend the capabilities and efficiency of higher-power launching apparatus and transmission systems. Similar to the shorter duration needs for ITER, a compact fusion power-plant will require continuous injection of high-power electromagnetic waves for plasma heating, plasma profile control, pre-ionization/startup, and plasma current drive.

Diagnostics have two important roles in preparation for a compact pilot plant. First, new measurement techniques are needed to provide the data to validate the physical models and simulation codes used to extrapolate to future devices. As noted in the NRC plasma science report,[57] "quite simply, we cannot understand what we cannot measure." Hence, diagnostic development is a key building block of the predictive understanding that will enable a compact fusion device, and these diagnostics will have to function reliably in the harsh neutron radiation environment near the burning plasma. New diagnostics are needed to replace those techniques incompatible with continuous production of fusion power. Measurements are needed to address the new issues associated with burning plasma experiments, such as detection of the alpha-particle population in ITER and erosion of material surfaces in the pilot plant.

In addition to measurement instruments, the plasma and fusion energy system will be actively controlled. Sensors will provide input to algorithms that control actuators in real-time to maintain the plasma in the desired state. Advances in machine learning and mathematical control theory may enable effective control of fusion plasmas despite imperfect knowledge of the plasma state.

> **Finding:** While continued research and development is needed to adapt enabling technologies for use in the compact fusion pathway, ongoing advances in heating, diagnostics, and control underway in support of ITER provide confidence that these technologies can be developed for higher-power longer-pulse fusion devices.

Blanket and Tritium Fuel Cycle Research

The integrated first wall and breeding blanket of a fusion reactor will need to operate at high temperature to ensure efficient conversion of fusion power into electricity in addition to generating tritium in the blanket. The tritium generated in the blanket, as well as the unburned tritium fuel from the plasma

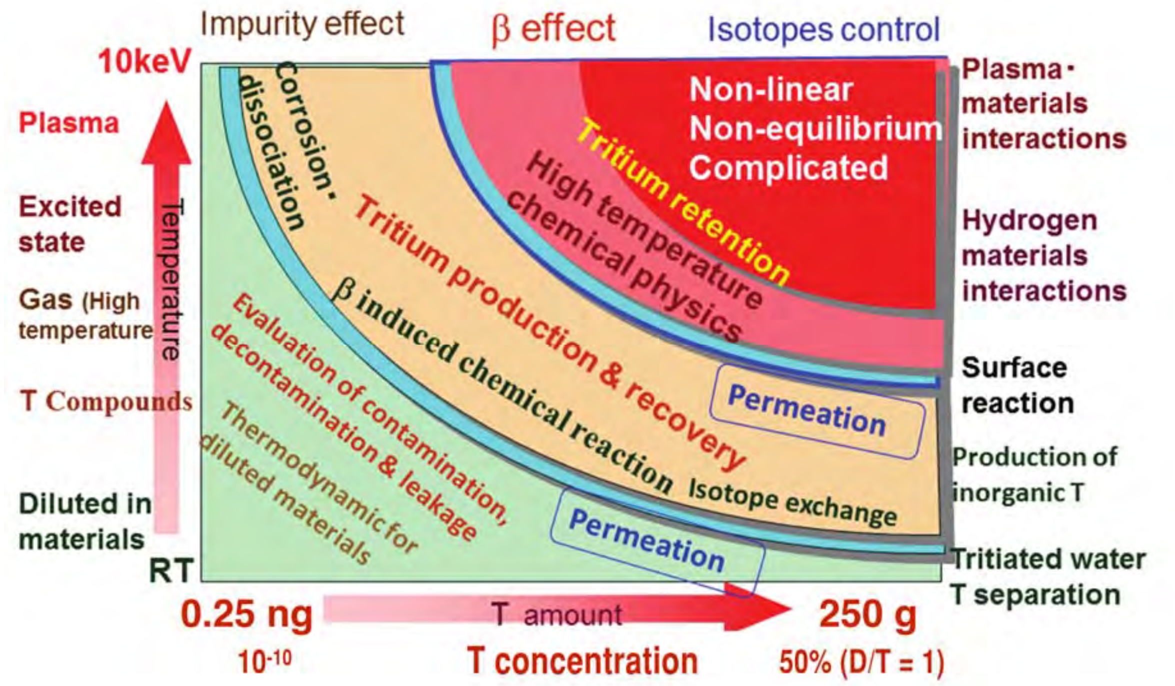


FIGURE 4.7 Science and technology required to establish a tritium fuel cycle. The diagram has blue bands depicting the need for two distinct tritium permeation barriers, as reproduced from Tanabe[64]. Commercial light water reactors release about 1 g T per year. 100 g of T is produced annually in a Canadian CANDU reactor, and a total of 20-25 kg T will be available for ITER operation.

exhaust, will need to be efficiently extracted and processed for re-introduction to the plasma. Although the performance, safety, and economics of a fusion system depend on successful power extraction and tritium breeding, these systems have a low technical readiness and significant uncertainty regarding performance and operating limits requiring technology advancement to extrapolate handling increasing tritium concentration and temperature, as illustrated in Figure 4.7.

Testing in prototypic environments is incredibly challenging. Because of the unique operating environment surrounding a burning plasma, the development of power handling and breeding blanket systems involves a complex set of interactions among numerous disciplines including materials, thermo-mechanics, thermo-fluids, magnetohydrodynamics, and corrosion chemistry. The complex, extreme fusion environment needed to test these components is not currently available. In addition to the science within each discipline, it is likely that synergistic effects among disciplines will be discovered when components are tested in a fusion nuclear environment.

The breeding and recovery of tritium as it is processed raises a number of safety concerns to protect workers, the public and the environment. Tritium is highly mobile, and can readily permeate through metallic components, especially at elevated temperatures. Tritium will have to be accurately tracked to assure safety and nonproliferation. The grand challenges of tritium require improved scientific understanding of many interconnected phenomena including permeation, radiolytic chemistry, surface science and kinetics, liquid metal magnetohydrodynamics, and mass transfer. Systems and processes should be developed that can efficiently and safely continuously process tritium at flow rates and quantities beyond current practice.

The United States has developed a potentially attractive family of blanket concepts, in which a dual cooled, lead-lithium eutectic alloy serves as both breeder and coolant. In this concept, the reduced activation ferritic steel integrated first wall and blanket structure have separate gas cooling and thermal- and electrical-insulating inserts based on silicon carbide composites that control the structural material temperatures at critical interfaces. However, this concept, along with the other solid and liquid blanket concepts that have been proposed, remain relatively immature due to a lack of research and testing capability to assess performance limits. A significant enhancement of research activities is needed to validate blanket concepts and the science and technologies of the tritium fuel cycle prior to constructing a compact fusion pilot plant.

The recent TEC report highlighted a number of technologies that show tremendous potential for fusion power development. These include advances in tritium fuel production in breeding blankets involving either the dual cooled liquid lithium concept or cellular ceramic blankets. Research into tritium fuel production would also address unresolved sintering problems in proposed ceramic pebble based fusion blankets. In terms of tritium extraction, the TEC report identified recent advances in electrolytic membrane extraction and permeable membrane extraction methods with the potential to efficiently process and extract tritium from liquid metal blankets. The TEC report also discussed the potential for a super-permeable metal foil pump that would effectively decouple the plasma and tritium plant operation and thereby reduce the size and inventory of the tritium plant substantially. While the TEC report noted these potentially transformative tritium fuel cycle technologies, it also noted the relatively low scientific and technical maturity of the fusion blanket system and the systems to manage the full tritium fuel cycle.

> **Finding:** Technical concepts needed to harness fusion energy are ready for design and testing. These concepts, along with innovations and promising new methods to separate and process tritium, will be essential to the development of a compact, lower cost fusion reactor.

PRE-PILOT-PLANT RESEARCH PROGRAM FOR THE COMPACT FUSION PATHWAY

Conceptual design studies for various compact fusion pilot plants have concluded that in addition to a burning plasma experiment research is needed to understand the interconnected science and technology for the high-field superconducting magnets and for the fusion components that surround the plasma, convert fusion power into useful heat, and breed and recover tritium. Important optimization is needed to configure the high-field HTS magnets and determine the burning plasma scenarios for high-power density uninterrupted operation at very low recirculating power. The most cost-effective configuration or shape for a compact fusion pilot plant has yet to be determined. Configuration options include divertor geometry, plasma aspect ratio, geometric parameters like elongation and triangularity and others that may improve the operation of the fusion power system. This “pre-pilot-plant” research program needs to be guided by an interdisciplinary systems-engineering effort to reduce the size and cost of the fusion development pathway and to attract industrial engagement in the development of fusion energy-based electricity for the United States. By the time construction of the compact fusion pilot plant takes place, industry should be prepared to deliver fully functioning industrially produced components fabricated using materials that have been appropriately qualified for use in the fusion pilot plant environment.

This section describes strategic elements within a pre-pilot-plant research program. They are intended to provide guidance for a program extending beyond ITER’s burning plasma experiments and leading to the construction of a compact fusion pilot plant having the lowest possible capital cost. Many technical details, research schedules, and issues pertaining to the proper balance between international and national research are beyond the scope of the committee’s study. However, the scientific and technical requirements for the pre-pilot-plant research program are well-documented through previous studies of a fusion nuclear science facility (FNSF) or a fusion pilot plant. Figure 4.8 illustrates the science and technology research elements of a “pre-FNSF” program that would still be necessary for the Compact Pilot Plant.

The pre-pilot-plant science and technology research program will need a coordinated engineering approach to guide a variety of laboratory scale experimental facilities, computational modeling and analysis, and collaborations with the international effort. New non-nuclear program elements will be

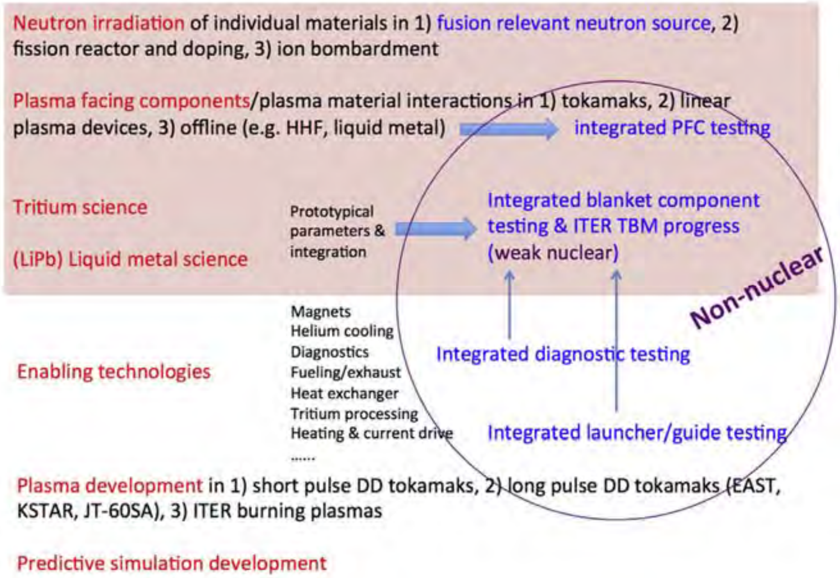


FIGURE 4.8 Elements of the "Pre-FNSF" research program leading to the design and construction of a fusion nuclear science facility (FNSF). Both nuclear and non-nuclear testing is shown. A similar research program is needed for a compact fusion pilot plant; however, an essential additional element of a plan to a compact fusion pilot plant is a program of engineering systems studies that guides research along the lowest-cost pathway. SOURCE: Figure 14 of C.E. Kessel, et al., "Overview of the fusion nuclear science facility, a credible break-in step on the path to fusion energy," Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.05.081.

needed for testing and evaluation of HTS fusion magnets, and for establishing critical design data for simultaneous thermo-mechanical loading in a high-temperature environment. A facility will be needed for evaluating the performance of divertor and plasma facing components at high temperature with representative particle and heat fluxes and compatible with high-performance and high-pressure fusion confinement. The mission requirements for this facility integrates the science and technology from the high-performance core to the divertor and expands upon the mission requirements for the Divertor Test Tokamak (DTT) proposed in both the 2015 FESAC Report on *Plasma Materials Interactions* and for construction in Italy.[58] The experimental demonstration of integrated uninterrupted high-power density magnetic confinement regimes is needed in order to validate the configuration and operation space for a compact fusion pilot plant. A new national research facility is probably needed to provide this. If so, the construction of such a new facility would occur after the most critical research missions of the national DIII-D and NSTX-U facilities are completed.

Fusion nuclear testing is essential for materials development and qualification for all aspects of fusion research. Fusion nuclear tests can include both fission and fusion relevant neutron exposure of individual material samples. A larger volumetric fusion neutron source can provide experimental data and initial nuclear testing of integrated first wall and breeding blanket systems as well as critical data on the effect of radiation damage and transmutation effects from a 14-MeV peaked neutron spectrum. While the strategies adopted in previous FNSF and DEMO pathways required qualification of all materials near the fusion core to the neutron fluence they will experience, a staged-approach to the operation of the compact fusion pilot plant may have simpler materials qualification requirements in a first-stage because of lower neutron fluences. This two-stage approach reduces the cost and accelerates fusion demonstration in the compact fusion pathway.

The key elements of the pre-pilot-plant research strategy, in addition to the burning plasma science and technology that will be learned from ITER operation, are:

- Systems-engineering for a compact fusion pilot plant,

- Advanced materials modeling for fusion technology,
- Testing of large-bore, high-field HTS magnets for magnetic fusion,
- Developing long-lifetime materials for fusion,
- Advancing tritium science and blanket technologies,
- A fusion neutron irradiation facility for prototypical materials qualification,
- Demonstrating sustained high-power-density fusion plasmas with optimized plasma exhaust configuration for compact fusion, and
- Continued development of fusion-enabling technologies needed to heat, measure, and control the burning plasma and to safely maintain the components within the compact fusion pilot plant.

Systems-Engineering for a Compact Fusion Pilot Plant

Options for a compact fusion pilot plant are at a pre-conceptual design stage, and iteration of the engineering design is needed to evaluate configuration options for reaching the optimum design goals. Systems engineering involves the integration of multiple science and technology realms including burning plasma science, configuration optimization and development of HTS fusion magnets, a compact blanket, licensing procedures, tritium processing technology, and enabling technologies like efficient plasma heating and current-drive systems. The design of the pilot plant should include both optimization of the burning plasma configuration and also considerations for efficient and low-cost balance-of-plant (BoP) systems needed for operating the plant. Experience from ITER operation will be important input to the design optimizations regarding plasma initiation, divertor science, burning plasma control, and other supporting fusion technologies. Examples include experience with ITER’s tritium-handling system, cryogenic systems, and measurement and control systems.

A systematic study is needed to explore configuration options for the compact fusion pilot plant. It should identify research needs and facility needs that can be addressed in the pre-pilot-plant program. Operational scenarios will need to be developed and supported by validated modeling incorporating state-of-the-art advances in coupled core-edge plasma simulations. Metrics for evaluating design options should include the capability for uninterrupted operations, very low recirculating power, demonstration of fusion electricity, a staged approach to tritium self-sufficiency, and a justified estimate for the construction cost. At the end of the concept design study, focused engineering design activities should commence with significant involvement of industry. Industrial experience could be developed by industrial participation in testing of component prototypes prior to the decision to construct a compact fusion pilot plant.

Advanced Materials Modeling for Fusion Technology

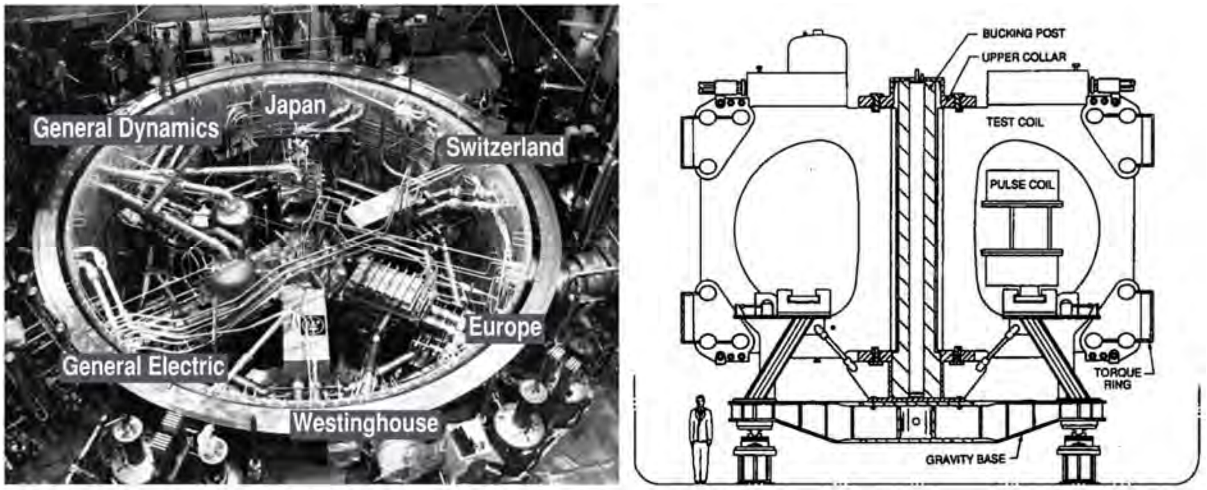


FIGURE 4.9 Photograph and schematic of the Large Coil Test Facility managed by ORNL at the International Fusion Superconducting Magnet Test Facility (IFSMTF). Six large-bore fusion magnets from industries in the United States, Switzerland, Europe Atomic Energy Community, and Japan operated for two years (1985-1987), reached stable operation at B = 8T, and successfully demonstrated low-temperature superconducting magnet technology for fusion. (Right) Photograph of all six superconducting magnets. (Left) A cross-section of the LCTF from "Large Coil Task Specifications." *Fusion Eng. and Design*, **7**, pp. 15-22 (1988).

The United States has made significant advances in multi-scale modeling of plasma materials interactions and high-energy neutron induced degradation of structural materials.[59,60,61] These multiscale models attack the complex materials degradation issues from both a “bottom-up” atomistic-based approach and a “top-down” continuum perspective, and they focus on the hierarchical integration of kinetic processes for species reactions and diffusion to model microstructure evolution over experimental timescales. The simultaneous use of both an atomistic and continuum approach has furthered the development of scale-bridging or multi-scale integration, and has led to fundamental insight into helium – hydrogen synergies controlling tungsten PMI as well as the long-term microstructural evolution due to radiation damage in structural materials[65]. However, it is important to note that these emerging modeling capabilities are in the early stages of development, and continued research activities are required to further develop this capability further. Central to the development of advanced modeling is to closely coordinate the modeling activities with experimental studies to provide both model validation and guidance for future modeling activities, as well as to design experiments to resolve specific scientific challenges such as simulating changes in multi-component surfaces and materials that are formed by erosion and re-deposition processes of PFC surfaces and neutron transmutation of structural materials.

Large-Bore, High-Field HTS Magnets for Fusion

The compact fusion pathway requires development of large-bore, high-field HTS magnets. Currently HTS magnet research and development is focusing on commercial production improvements, characterization of conductor performance, and the scale-up and integration of the magnet assemblies and components, such as the cables needed to fabricate full-size fusion-class magnets.

On March 9, 2018, MIT and a newly formed private company, Commonwealth Fusion Systems (CFS), announced the start of a staged research effort for fusion experiments and fusion power systems based on advances in high-temperature superconductors.[62] Other efforts to develop large HTS magnets include the Magnet Development Program sponsored by the U.S. DOE Office of High Energy Physics, the National Institute for Fusion Science (NIFS) at Toki, Japan, the National High Magnetic Field

Laboratory (Tallahassee, FL), which announced the world's largest magnetic field generated with superconducting solenoid in December 2017, and several European efforts including CERN, CEA (FR), KIT (DE), University of Geneva (CH), University of Twente (NL) and Bruker HTS (DE).

Because of the importance of HTS magnet development for fusion, an opportunity exists to initiate a large-coil HTS test facility modeled after the Large Coil Test Facility (LCTF) that was hosted by the ORNL in the 1980s. Figure 4.9 shows a photograph of the installation of one of six LTS magnets and a schematic showing the cross-section of the LCTF. The international magnet test facility evolved from the Large Coil Project (LCP) imitated through contracts awarded to industrial teams led by GDC (General dynamics Convair Division), GE (General Electric Company) and WH (Westinghouse Electric Cooperation). Later, the International Energy Agency (IEA) Fusion Power Coordinating Committee (FPCC) sponsored an international agreement with partners of EURATOM, Switzerland and Japan. Each of the six coils that were tested had different features but met equivalent magnet requirements. The GDC coil used Nb_3Sn, while the other five coils used NbTi as the superconductor. A U.S. sponsored HTS test facility would likely attract participation from industries from several nations. Such international cooperation, along with the opportunity to partner with private industry within the US, would be quite useful for accelerating optimizing HTS coil design as well as identifying the most cost-effective manufacturing method.

In addition to a large coil HTS test facility, several important smaller scale components, including a new, very near-term test facility, are needed if the United States is to play a leading role in superconducting magnet development for fusion. The purpose of such an additional facility is to allow testing of full size HTS jacketed cable samples at high field over a range of temperatures and currents. This HTS sample test facility has been strongly urged by United States superconducting magnet researchers. It would be much less costly than a full coil test facility, and research use may include non-fusion applications of HTS magnets including those for high-energy physics. This relatively small facility has the potential to substantially speed up magnet development since new designs and concepts can be rapidly tested under realistic conditions with small sample sizes. As of now, testing of such cable samples take place either in NIFS (Japan) or SULTAN (Switzerland), neither of which has the high field capabilities needed for HTS. Furthermore, the United States has little control over the prioritization of usage time at these facilities of other nations. The other equally important components of a U.S. HTS program include the development of magnet quench detection and protection systems, demountable coil development and testing, conductor stress/strain management, characterization of radiation resistance, and continued research and development of advanced HTS materials.

Developing Long-Lifetime Materials for Fusion

One of the keys to understanding and controlling plasma material interactions in the divertor and plasma facing components is to collect data on the evolution of material surfaces during and following long-term plasma exposure. The United States program has contributed significantly to this research through PMI experimental studies based on the PISCES facility.[63] Additional research is needed to explore very long duration exposure under conditions of high heat and particle flux with a representative geometry. The opportunity exists for a cost-effective linear plasma material interaction test stand that would utilize a high-intensity radio frequency (RF) plasma source for experimental PMI studies. The new linear test stand should be able to operate uninterrupted for many days and expose targets at glancing angles with an applied magnetic field in order to test models of the plasma-material sheath, the acceleration of ionized impurities, emission of secondary electrons, while maintaining ion and neutral fluxes directly relevant to a fusion divertor.[64] The knowledge gained from PMI tests stands would need to be coordinated with plasma divertor research and inform the selection of divertor materials needed to sustain a high-power density fusion plasma with an optimized plasma exhaust.

Advancing Tritium Science and Blanket Technologies

A commercial source of fusion electricity requires a closed tritium fuel cycle. In order to fully realize commercial fusion power, the science and technology of tritium needs to be developed. This includes all tritium processes and the methods needed for safe operation and benign environmental impact. Virtually all of the technologies related to the tritium fuel cycle are at low technical readiness, with uncertain parameters that describe tritium migration through materials and across interfaces, its retention in bulk solids and liquids, and retention and behavior in plasma facing materials. Building technical readiness for fusion power requires a program of materials testing and component performance when exposed to fusion neutrons.[65,66]

In a fusion power system, the breeding blanket is a critical component that consists of a set of modules covering the interior of the fusion vacuum vessel, capable of supporting a high heat load and an intense neutron flux.[67] The breeding blanket will need to (1) assure self-sufficiency of the fusion reactor with regard to tritium, (2) maximize the net efficiency of the power plant, (3) act as a radiation barrier, and (4) act as structural barrier to limit dispersion of the tritium and potential activation products suspended in the coolant.[68]

ITER provides an opportunity to answer questions regarding tritium processing at large scale within the fueling/exhaust tritium loop. The ITER Test Blanket Module (TBM) program is the first opportunity to study whether tritium can be generated in a blanket and whether heat can be extracted for power production.[69] Although the amount of bred tritium to be handled will be relatively low, due to a small testing area and low plasma duty cycle, the tritium transport processes involved in the TBM program are prototypical of the fusion blanket tritium fuel cycle, including deuterium and tritium neutral ion flux implantation and the resulting transport and permeation under prototypical tokamak plasma facing surface and operating conditions.

The complexity involved in understanding the behavior of breeding blanket concepts in the fusion environment has led to a rather detailed planning for TBM testing program in ITER.[70] During the non-nuclear phase of ITER operation, the TBM testing objectives are to (1) test the electro-magnetic response, (2) verify the test blanket system operation in the ITER operating environment, (3) demonstrate the cooling capability and TBM resistance to ITER disruptions, (4) obtain data required for the nuclear licensing process, and (5) confirm that the TBMs do not jeopardize the quality of plasma confinement. During the nuclear phase with operation with deuterium and deuterium-tritium plasma, the main ITER TBM objectives are to (1) test the thermal-neutronic behavior, neutronic-tritium/thermo-mechanic response and integral performance of the modules, (2) validate the predictions with modeling codes and nuclear data, (3) assess the TBMs thermo-mechanical behavior, (4) demonstrate the tritium management capability, and (5) demonstrate TBM performance for an extended period of time.

At the ITER Organization (IO), the ITER Test Blanket Module (TBM) program will provide an opportunity for testing tritium breeding blanket concepts that would result in tritium self-sufficiency, an extraction of high-grade heat and net electricity production in future fusion reactors. Although all of the TBM Arrangements were signed in 2015, the ITER International Organization (IO) has not made a final determination on proceeding with the ITER Test Blanket Module (TBM) program, and the decision to install the TBM on ITER requires signing additional legal arrangements dealing with all TBM phases through decommissioning.

The United States is not currently a partner in the ITER TBM Program. Whether or not the U.S. becomes a supporting partner in a TBM activity would need to be determined after further consideration of the schedule and capabilities of the ITER TMB activities, as well as the goals of the new national blanket technology program are defined. Should the United States decide not to seek supporting partnerships on one or more ITER TBMs (assuming they are approved by the ITER IO), then the United States will forego access to and experience with the resulting demonstrations and will need to develop this experience through the national blanket technology program. If an ITER TBM partnership collaboration were initiated, the United States, for example, could contribute critical property data such as recombination coefficients, tritium diffusivity in PbLi, MHD mixed convection on tritium transport, and tritium transport within permeation barrier coatings, through small scale laboratory tritium experiments. Additionally, international collaboration on the various aspects of the tritium fuel cycle and the accompanying areas of fusion nuclear materials, plasma facing materials, fusion nuclear science, and enabling technologies requires serious consideration. These objectives are critical steps toward developing working breeding blankets for future fusion concepts.

Other opportunities exist in blanket and tritium fuel cycle research that could be conducted in parallel with the ITER activities. Non-nuclear testing can be conducted to advance understanding of thermo-solid and thermo-fluid mechanics, tritium extraction and migration, and some aspects of a fuel cycle development facility. The thermal-fluid testing would incorporate surface and volumetric heating with high magnetic field strength and representative coolant flow rates. This non-nuclear fuel cycle research and development investigates only deuterium/hydrogen isotopes to advance the required technologies for tritium extraction and processing. Because fusion neutron irradiation will change materials properties, such as barriers to tritium penetration, beneficial synergies should be explored, such as the possibility that enhanced trapping of tritium in solid material due to damage or even the nanostructured particles introduced may enhance the material's radiation resistance. Access to a neutron irradiation facility is required for initial data on neutron exposure effects on welds, component lifetimes, and reliability.

Fusion Neutron Irradiation Facility

The fusion nuclear engineering community has long advocated a dedicated fusion neutron irradiation facility for acquiring material irradiation test data in a simulated fusion environment for design, licensing, construction and safe operation of fusion structural materials and, also, for benchmarking radiation responses of materials with computational material science. Existing neutron irradiation sources include accelerator-driven sources, like the SINQ Target Irradiation Program (STIP) at the Swiss Paul Scherrer Institute (PSI), and fission-based sources like the High Flux Isotope Reactor (HIFR) at ORNL. Options for fusion neutron irradiation facilities with a 14 MeV fusion neutron spectrum do not now exist although proposals for such a source include a plasma-based volume neutron source (VNS) or accelerator-based facilities with either gas, liquid or solids targets.[71] Based on joint Japanese and European research in the framework of the Broader Approach (BA) agreement, the IFMIF-DONES (International Fusion Materials Irradiation Facility - DEMO-oriented Neutron Source) is currently being developed for the irradiation of temperature controlled capsules containing test specimens filling a 54 cc volume. The capsule-averaged structural damage rate expected for IFMIF-DONES reaches 15 dpa/fpy.[72]

Opportunities should be explored to provide a larger-volume fusion irradiation environment that would study and increase the technical readiness level of breeding blanket components and systems prior to the construction of the compact fusion pilot plant. A low-cost material testing facility has been proposed for near-term fusion materials research.[73] Recognizing the need to conserve resources, fusion engineers have proposed either a low-cost linear mirror device for blanket testing or, when mirror research was abandoned in the U.S., a driven tokamak.[74,75] New results in the gas dynamic trap (GDT) mirror device at Novosibirsk have revived interest in the mirror option.[76]

The licensing requirements for the first and second phases of the compact fusion pilot plant need to be determined early in its planning. If irradiation data are only required for structural material samples and welds, then full-size fusion components can be tested as part of the fusion pilot plant research program. If larger volume irradiations are required, then program planning would need to design and construct a cost-effective plasma-based neutron source. In particular, determining whether construction of a volumetric fusion neutron irradiation facility using a magnetic mirror device, or an alternate configuration, would more rapidly advance the technical readiness and lower the cost of the compact fusion pathway needs to be answered as part of the systems engineering studies.

Sustaining High-Power Density Fusion Plasmas with Optimized Plasma Exhaust

The United States has made significant contributions to the development and understanding of high-performance, steady-state burning plasma operating scenarios that will be used in ITER to demonstrate fusion power gain for pulses of several minutes. However, the compact fusion pathway requires further advances in fusion performance to achieve high power density in a small-sized device with integrated core-edge plasma scenarios capable of uninterrupted operation. This approach is inspired by recent experiments, which were motivated by theoretical studies, that demonstrated record performance on Alcator C-Mod (world record plasma pressure) and DIII-D (high equivalent fusion gain) through optimization of the pedestal performance. Separate experiments have demonstrated high-performance steady-state scenarios with no ELMs and the sustainment of high bootstrap fraction scenarios with internal transport barriers at near zero rotation. Further, the impact of reduced aspect ratio and improved boundary shaping on access to regimes of enhanced pedestal confinement and stability will be investigated utilizing NSTX-U operation at higher plasma current and toroidal field. Additionally, theoretical studies have indicated the distinct advantages of high-field side-launched RF in obtaining much higher current drive efficiencies, which if realized could lead to more efficient fusion systems.

The investigation of compact burning plasma conditions will require increased values of normalized size, $R \times B/T^{1/2}$, while maintaining achievable levels of plasma collisionality and normalized plasma pressure, $\beta \sim nT/B^2$. Currently the two U.S. national facilities (DIII-D and NSTX-U) are operating at relatively low toroidal fields (B = 2.2 T in DIII-D and B = 1 T in NSTX-U). A device built at the size of DIII-D but with a much larger magnetic field (about $B \sim 4$ T) and with larger heating power ($P_{heat} \sim 50$ MW) would be a potential facility. Opportunities exist to extend the capabilities of the U.S. national facilities. High-performance fully non-inductive scenarios can be explored on NSTX-U[77] and with planned upgrades of DIII-D[78] and NSTX-U.[79] A follow-on national facility, which combines the research efforts of the DIII-D and NSTX-U, could provide new advanced tokamak studies closer to burning-plasma conditions.[80] This would involve a substantial upgrade, or a new facility.

A key issue in assessing the compact fusion pilot plant is confinement performance scaling at high β_N as the normalized device size, $R \times B$, increases. High β_N reduces the size of the fusion device and increases the bootstrap current fraction, thereby reducing the current drive power and improving the overall efficiency of the pilot plant. While ITER and JT-60SA will provide some information about performance improvements with increasing β_N, plasma edge pedestal models predict that the highest performance, and hence highest fusion power density, will be achieved with optimal shaping of the plasma, including aspect ratio, triangularity, and elongation. DIII-D and NSTX-U are well positioned to provide key information on the choice of the required parameters for a follow-on high-power density research facility needed to establish the science and technology basis for the compact pilot plant. This approach would also enable exploration of the physics benefit of high field operation, particularly the impact on improving plasma confinement, which is synergistic with the high temperature superconductor (HTS) research. In fact, practical experience could be gained with smaller HTS TF magnets if the magnet R&D delivers such a capability on the necessary timeline. Considering the importance of long-pulse advanced tokamak operation to the compact fusion pathway, the availability of HTS magnets would be significant, but its use critically depends on the outcome of timely HTS magnet development.

Theory and Simulation

Integrated simulation has long been part of fusion energy research, and recent years have seen a tremendous improvement in the ability to perform simulations with increasing physical fidelity. Theoretical and computational models developed in the United State have substantially improved the ability to predict plasma confinement, control plasma stability, and enhance fusion energy performance.[81,82]

In addition to integrated simulation making important contributions to developing burning plasma science with ITER, advancement along the compact fusion pathway will benefit from research on integrating more multiple physics, multiscale phenomena, and higher-fidelity algorithms into simulations as well as further expanding the simulation capabilities toward prediction and design. These advances in theoretical and computational models, which enable the development of whole device modeling with increasing physical fidelity, have been facilitated by the rapid growth in computational capabilities and the U.S. DOE Office of Science initiatives that have encouraged partnerships among fusion, applied mathematics and computer science researchers.[83]

High-fidelity whole device simulations will improve physics understanding and further enable optimization of the high density, high performance plasma core coupled to a detached divertor. Continued research investments in whole device modeling should improve the fidelity of kinetic simulations, help develop model hierarchies for incorporating disruption and boundary physics, allow incorporating the interactions of fast particles with thermal plasma waves and instabilities, the strong coupling of core transport to sources and instabilities, and improve the coupling of the plasma surface interactions and boundary plasma physics to the pedestal and plasma core. Advances in whole device models, as well as individual physics models, are anticipated to enhance the capability of probabilistic whole device modeling to assess the likelihood of key physical transitions such as those leading to plasma disruptions, to optimize operational conditions for achieving specific fusion energy gains, and to optimize or even increase the divertor heat flux thresholds.

Stellarator Contributions to Compact Fusion Energy

The compact fusion pathway is based on an advanced tokamak configuration operating at sufficiently high normalized beta and sustained continuously, without the need for significant current drive power, because of self-generated bootstrap current. The tokamak configuration has dominated the world's fusion research program. Fusion performance achieved with the tokamak configuration is superior to other magnetic configurations; however, theory, simulation, and experiments with the stellarator configuration is strongly related to the tokamak and can contribute to the integrated science and technology needed to design the compact fusion pilot plant.

The stellarator concept was invented in the U.S. and, in some configurations, the confinement field can be produced entirely by the external magnetic coils. Two large stellarator devices operate with superconducting magnets: the Large Helical Device (LHD)[84] in Japan and the Wendelstein-7X (W7-X)[85] stellarator in Germany. A smaller, helically symmetric stellarator (HSX), built with copper magnets, is located at the University of Wisconsin in the United States. As shown in Figure 4.5, the plasma duration of the LHD stellarator has achieved pulse lengths comparable to what is expected in ITER, except at much lower fusion gain. Because most of the rotational transform of a stellarator is generated from external coils, the stellarator magnetic configuration does not require current drive power. Additionally, because the magnetic configuration is controlled primarily with external magnets, a transient confinement loss due to plasma instability should avoid all plasma current disruptions and the generation of runaway electrons.[86]

W7-X has a high aspect ratio ($A > 10$) with a large major radius, $R = 5.5$m. The W7-X stellarator is called a "heliac," and HELIAS fusion reactor studies show this type of configuration leads to large fusion power systems.[87,88] Currently, the United States is an active collaborator in the W7-X experiment, and stellarator research using W7-X contributes to understanding of all aspects of toroidal magnetic confinement, including energy and particle transport, energetic particle physics, and divertor science and technology. The two large stellarators with superconducting magnets (see Fig. 4.5) have achieved operating conditions comparable to the superconducting tokamaks, EAST (China) and KSTAR (ROK), when operating for about one-minute pulses. These superconducting fusion research facilities provide opportunities to develop the science and technology needed for continuous operation and to learn from the comparison between axisymmetric and three-dimensional magnetic geometry.

While the long-pulse capabilities of the superconducting LHD and W7-X stellarators contribute to the knowledge needed for the long-pulse operation of the compact pilot plant, stellarators with "hidden symmetry," either quasi-axisymmetry (QA) in the toroidal direction or quasi-helical-symmetry (QH) in the helical direction, will also contribute to understanding of the role of symmetry in high-performance magnetic confinement and stability through the development and validation of predictive models. As presented to the committee,[89] the toroidal magnetic confinement with quasi-symmetry have not been well-tested in the laboratory, but opportunities exist for an optimized intermediate-scale research facility that may impact the national effort to design a compact fusion pilot plant. Such optimization is expected to be useful to generate flow in the quasi-symmetric direction and hence to enhance confinement by flow shear suppression of turbulence. In a quasi-symmetric stellarator, unlike the heliac configuration, plasma currents will change the magnetic structure as plasma pressure increase. Quasi-symmetric stellarators might help validate models to predict fusion performance and improved optimization of a compact fusion pilot plant. Because the only operating quasi-symmetric stellarator is located in the United States and, more importantly, because quasi-symmetric stellarators might lead to improved designs for a compact fusion confinement system, opportunities exist to explore this configuration and validate the physics of three-dimensional magnetic fields and quasi-symmetry for toroidal magnetic confinement.

Fusion Enabling Technologies for Plasma Heating, Current Drive, Measurement and Control and Safe Maintenance of Core Components

The compact pathway to fusion requires higher magnetic fields and long, uninterrupted plasma operation. Continued development of fusion enabling technologies include: higher frequency gyrotrons and transmission systems in the range of 250-336 GHz, higher power, more compact antenna/wave launching systems for a compact pilot plant, advancement in diagnostic and plasma control systems, and the implementation of remote maintenance of fusion components located near the burning plasma. Before the operational pulse times of fusion research facilities can significantly increase, research and development of the associated plasma heating, plasma current drive, and plasma control systems are required. Examples of such research are described earlier in this chapter, and Chapter 2 described ongoing research activities for robust current drive technologies, like injection of high-frequency "helicon" waves.

SUMMARY

This chapter describes the interconnected science and technology research required within an expanded U.S. burning plasma research program in the near and mid-term leading to construction of a compact fusion pilot plant at the lowest possible capital cost.

> **Finding:** Recent advances motivate a new national research program leading to the construction of a compact fusion pilot plant at the lowest possible capital cost that will accelerate the fusion development path. Significant progress has been made to predict and create the high-pressure plasma required for such a reactor. This progress combined with opportunities to develop technologies for fusion, such as high-temperature superconducting magnets and advanced materials, now make a compact device technically possible, affordable, and attractive for industrial participation. This finding is supported by the following:

- Although additional research, including magnet engineering research, is needed to demonstrate the viability of the compact pathway to fusion power, the combination of new high-field superconducting magnet technology with advanced burning plasma science is a significant opportunity to decrease the size and cost of a magnetic fusion power system.
- While methods to remove heat from the divertor and reduce material erosion due to plasma sputtering remain active research areas, current understanding of divertor scaling shows that the

compact fusion pathway at higher field and lower total power may benefit power handling solutions for fusion energy.

- While significant progress needs to be demonstrated to achieve uninterrupted operation of a high-performance fusion confinement device, the higher magnetic field in the compact fusion pathway appears to allow operation at high fusion power density, high poloidal beta, and high bootstrap current fraction more easily than other pathways to commercial fusion power.
- While additional research and development is needed to establish the technical basis for large high-field HTS magnets, the growing industrial capability to produce HTS conductor, opportunities to partner with industry and other U.S. DOE program offices, and the rapid progress in HTS magnets promise significant reductions in the size of magnetic fusion devices and supports the compact pathway to fusion development.
- While advanced manufacturing and complex material component design have transformative potential, research is required to move beyond the early stage of developing these alloys and composites. This includes radiation effects, chemical compatibility and corrosion, unknown response to plasma material interactions and tritium permeation, and component performance and degradation in the complex neutron, plasma material and thermal-mechanical loading conditions. Studies should proceed from relatively simple single-variable experiments to very complex, fully integrated, multiple variable tests.
- While continued research and development is needed to adapt enabling technologies for use in the compact fusion pathway, ongoing advances in heating, diagnostics, and control underway in support of ITER provide confidence that these technologies can be developed for higher-power longer-pulse fusion devices.
- Technical concepts needed to harness fusion energy are ready for design and testing. These concepts, along with innovations and promising new methods to separate and process tritium, will be essential to the development of a compact, lower cost fusion reactor.

Based on these findings, the committee offers the following recommendations:

Recommendation: Along with participation in international fusion research, including the ITER partnership, the U.S. DOE OFES should start a national program of accompanying research and technology leading to the construction of a compact pilot plant, which produces electricity from fusion at the lowest possible capital cost.

Recommendation: In the near- and mid-terms, the U.S. Department of Energy should resolve critical research needs for the construction of a compact fusion pilot plant:

- **Understand the science, production, and control of burning plasma at the scale of a power plant through participation in ITER.**
- **Demonstrate the science and engineering needed to sustain a magnetically confined plasma having the high-confinement property and compatible plasma exhaust system that are needed for a compact fusion pilot plant.**
- **Advance high-critical-temperature superconductors (HTS) and demonstrate the ability to achieve high magnetic fields using large, fusion-relevant coils.**
- **Expand significantly the U.S. research program in fusion nuclear technology, advanced materials, safety, and tritium and blanket technologies needed to fully enable fusion energy.**
- **Develop promising innovations in burning plasma science, such as optimized stellarator configurations and innovative approaches for a low-cost fusion irradiation facility, and fusion engineering science that reduce the cost and improve the fusion concept as a source of electricity.**

Recommendation: In addition to study of a burning plasma, new research facilities should be built to increase the technical and scientific readiness of critical capabilities needed to construct a compact fusion pilot plant. This will require retiring one or more existing facilities as they complete their most important goals.

Recommendation: In recognition of the significant challenges that needs to be addressed for the construction of a compact fusion pilot plant facility capable of electricity production, the U.S. DOE OFES plan for a pilot plant should have a two-phase approach. These objectives of these two phases are:

- **In the first phase, the pilot plant should be capable of demonstrating fusion electricity production for periods lasting minutes and establish the feasibility of electricity production in a compact fusion system including the assessment of plasma material interactions, tritium safety, pumping, recycling, breeding, and extraction.**
- **In the second phase, the pilot plant should be capable of uninterrupted operation for many days allowing fusion materials and component testing consistent with a commercial power plant, including full fuel cycle blanket testing.**

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5

Strategic Guidance for a National Program for Burning Plasma Science and Technology

This chapter summarizes previous chapters in the context of the committee’s strategic guidance for a national program for burning plasma science and technology covering the next several decades. The committee’s two main recommendations are elaborated. This chapter summarizes program elements, an approximate research timeline, a response to a decision to withdraw from ITER, and budget implications of the committee’s guidance.

This plan has two parts.

- First, the United States should seek full benefit from continued participation in the ITER project as the nation’s burning plasma experiment.
- Second, the United States should start a national program of interconnected science and technology research extending beyond what will be accomplished with ITER and leading to construction of a compact fusion pilot plant at the lowest possible capital cost.

Together, these two research efforts establish the scientific and technical feasibility of fusion power and advance the fusion program from its current feasibility stage along a cost-effective path to the production of electricity from fusion. The strategic guidance strengthens United States capabilities in burning plasma science, materials science, fusion nuclear science, and engineering science, continues engagement in the international effort, and promotes innovation and the involvement of industry.

ITER: EXTENDING THE FRONTIERS OF BURNING PLASMA SCIENCE

At the foundation of the U.S. strategy is the production, study, and exploitation of a burning plasma. This regime is characterized by plasmas that are dominantly self-heated by the particles generated by the fusion reactions. Methods to control plasma stability, plasma interactions with first wall materials, plasma confinement, and fusion power output will be tested. Theoretical predictions of energetic particles produced by fusion reactions and methods to sustain a burning plasma will be explored and validated. Equally important are gains in fusion engineering science and industrial capability that result from construction of the world’s first burning plasma research facility at the scale of power plant.

The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States receives full benefit from the technology that will establish the feasibility of fusion while providing only a fraction of the financial resources

Active participation in the ITER project is necessary for the U.S. to derive full benefit from the ITER project. The committee is not aware of any credible alternative that might achieve burning plasma conditions sooner. Effective participation in ITER requires that the U.S. continue to invest in domestic tokamak facilities and research to address operational issues for ITER and prepare the physics and fusion technology needed to enable next step devices. United States researchers are providing solutions and technical support for successful preparation and operation of the ITER facility. In some areas the United States is uniquely able to provide essential information. Even at this stage of ITER preparation, U.S. fusion research experiments provide knowledge needed to refine burning plasma operating scenarios, to finalize the designs for magnets to control transients, to develop the systems used to mitigate the adverse impact of plasma current disruptions, and to predict the response of the divertor during the expected periods of high plasma heat-flux. Later, during ITER operations, opportunities will exist for the United States to take leadership in upgrading capabilities and the development and testing of ITER operating scenarios that may expand ITER's scientific impact on the physics and predicative design tools used to lower the cost of fusion development.

Ongoing research targeted to resolve issues related to plasma control and transient reductions should continue. Recent research has been important in developing the ITER plans, which are guided by new techniques to suppress edge localized modes (ELM) using external control magnets, injection of small pellets of frozen hydrogen, and operation in regimes that are naturally stable to ELMs. A hierarchical approach is needed for mitigating adverse effects of plasma current disruptions, including design of scenarios that are naturally disruption resistant, predictive algorithms for assessing the plasma stability, control tools for stabilizing large scale MHD, recovery modes for dealing with off-normal faults and reliable mitigation tools when a disruption cannot be avoided. The two largest research facilities within the United States, NSTX-U and DIII-D, are well-poised to address these issues in the near term. Examples of additional research tools include additional plasma heating and plasma current drive systems, expanded magnet systems for precision plasma control, and improved methods to measure plasma phenomena including those diagnostics capable of fully exploiting the physics of plasma current disruptions.

While reaching the frontier of burning plasma science will establish the feasibility of magnetic fusion energy, the full benefit from participation in ITER will result from opportunities to develop and test burning plasma science in order to maximize the potential of a compact fusion pilot plant. Recent advances in theory and simulation validated by results from United States experiments have already suggested ways to optimize ITER performance. A strong focus on high performance steady-state scenarios in ITER will advance understanding of the strongly coupled system, where the heating source (primarily fusion produced alpha particles) and current drive (primarily pressure-driven bootstrap current) are both strongly coupled to confinement and energetic particle physics. Advances in understanding toroidal magnetic confinement, plasma control, and integrated solutions to whole-plasma optimization point to improvements beyond the ITER baseline and show how careful design and simulation can be used to lower the cost and accelerate fusion energy development.

The United States research participation with ITER should develop and test burning plasma scenarios, validate predictive simulation models, and gain engineering experience that will contribute to reliable operation of a compact fusion pilot plant.

BEYOND ITER: SETTING THE NATION'S FUSION ENERGY GOAL

As discussed in the committee's Interim Report and the technical analysis in the previous chapters, now is the right time for the United States to develop a national strategic plan for fusion energy that benefits from its investment in burning plasma research and takes leadership in the development of fusion electricity for the nation's future energy needs. The adoption of such a plan provides a grounding for strategic funding decisions and priorities within the national program and helps foster innovation toward commercially viable fusion reactor designs. Additionally, a national fusion energy goal guides national research and innovation programs, helps to engage all participants in the fusion endeavor in the United States, from universities, to national laboratories, to industrial partners, and sets the national priorities of our partners, enabling them to develop key areas of unique expertise.

Many reasons justify the readiness to develop a national strategic plan for fusion energy. Through the work of the United States and other nations, the ITER project is "back on track," and confidence has increased that burning plasma science will succeed in its mission. In contrast to the strategic planning proposed more than a decade ago, today the international community is stronger. The world effort has achieved rapid scientific and technical progress, and significant efforts are now underway by our international partners to move fusion beyond ITER toward commercial fusion energy. If the United States seeks to maintain a leading role in the pursuit for abundant fusion power, the development of a national strategic plan for fusion energy that spans several decades is necessary.

Most importantly, the reason behind our committee's recommendation is scientific progress, technical readiness and the opportunities presented by recent advances in fusion-relevant technologies. Understanding of toroidal magnetic confinement is now highly advanced: performance beyond the ITER baseline can now be predicted and new science shows how advanced knowledge and simulation can be used to speed fusion development. Additionally, new technologies (largely developed outside fusion) show great promise to reduce the size and cost of fusion power systems and reduce the cost of fusion research and further progress. Today, with many of the complex physical processes of magnetically confined plasma becoming better understood and the first phase of ITER construction more than half complete, the most critical fusion science research needs are interdisciplinary, combining burning plasma science with materials science, fusion nuclear science, and engineering science. These interconnected science challenges require a comprehensive strategic plan that looks beyond the demonstration of feasibility expected with the ITER device and addresses all of the challenges for developing fusion power. With the initial operation of ITER scheduled to begin within a decade and with the expectation that controlled fusion will be demonstrated in ITER, now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take leadership in the development of fusion electricity for the nation's future energy needs

TOWARD FUSION ELECTRICITY: THE COMPACT FUSION PILOT PLANT

The committee's two main recommendations address the nation's strategic interest in realizing economical fusion energy in the long term. First, as described in Chapter 3, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant. Second, as described in Chapter 4, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant which produces electricity from fusion at the lowest possible capital cost. Implementation of both recommendations require essential research using facilities and programs within the United States and continued active partnership with the international effort.

The committee considered several strategic pathways for the nation's long-term demonstration of fusion electricity. The objective of each path was fusion electricity, but the size, priority, and number of research facilities were different. For example, a Fusion Nuclear Science Facility (FNSF) does not need to make electricity, but instead focuses on the materials science and fusion nuclear science to develop materials that can survive the harsh environment surrounding a fusion system and it enables scientists to understand and control the operation of a burning plasma for many days. However, a FNSF would need to be followed by a second, larger facility to demonstrate fusion electricity. Other nations are pursuing a large, next-step fusion device, called a Demonstration Fusion Power Plant (DEMO).[1,2,3] A fusion DEMO would be capable of producing electricity, operating with a closed fuel-cycle and be the single step between ITER and a commercial reactor. This definition of DEMO calls for larger devices with the mission to produce significant net electricity, establishing routine electricity production and maintenance in order to convince utility companies (and other associated investors) that all aspects of the power source are credible, reliable, safe, and ultimately profitable. Previous committees of the National Academies and of FESAC have recommended that the United States develop a strategic plan leading to either an FNSF or to a DEMO. By contrast, this committee's recommendation recognizes the advantages for a reduced cost pathway to fusion energy demonstration and the scientific and technical opportunities that make this pathway possible.

Based on scientific progress and the expectation of innovations in technologies that will decrease the size of the magnetic fusion reactor and, as a consequence, also reduce both the capital-cost and construction time, the committee's strategic guidance for the United States is to target a pilot plant producing power similar to the power levels expected in ITER but in a device much smaller in size and cost and employing design improvements that allow net electricity production. The recommended strategy is faster and less costly than a two-step approach that requires both the construction of an FSNF and a follow-on DEMO device to produce electricity. The recommended strategy is also less costly than those proposed by other nations, which involve a single large DEMO device. This is because the goal of the compact fusion pilot plant is to incorporate science and technology innovations into a single facility, with a staged research plan, that will produce electricity from fusion at the lowest possible capital cost.

This compact fusion pilot plant would be a pre-commercial research facility with a burning plasma at its core and surrounded by a blanket to capture fusion heat and neutrons. In addition to the production of fusion electricity, the pilot plant would ultimately be capable of uninterrupted operation for weeks and produce tritium, the fusion fuel, from lithium-containing blankets that surround the plasma. The compact pilot plant would be a staged facility and constructed at lower capital cost than previously consider for fusion demonstration devices. The first stage will establish the capability of uninterrupted operation at high-power density in a compact device. The second stage would operate at high fusion power and demonstrate the safe production and handling of the tritium fuel required for sustained power. As a pilot plant, its purpose will be learning, but the knowledge obtained would be sufficient for the next-step to be commercial fusion power systems.

By starting a national research program toward a compact pilot plant, critical science and technology research can be ready in time to use the knowledge learned from ITER operation to demonstrate electricity production by mid-century.

2020-2035: REMOVING THE BARRIERS TO LOW-COST FUSION DEVELOPMENT

The cost of fusion electricity is driven principally by its capital cost and by how many hours the plant can run each year. Key to the achievement of low-cost fusion development are four research challenges: (1) the fusion power density should increase beyond that obtainable in ITER, (2) uninterrupted steady-state operation needs to be demonstrated while learning how to handle reliably the high levels of heat escaping from the plasma, (3) innovations should be encouraged and developed to significantly reduce the size of the fusion power system, improve component lifetime, simplify maintenance, and lower construction cost, and (4) blanket technologies should be developed and tested to efficiently and safely breed tritium and extract high quality heat.

Resolving these barriers to low-cost fusion development will require the design and operation of new facilities and continued engagement in the international effort. Facility decisions should be guided by cost-effective opportunities to achieve critical program goals and by unique opportunities for world-leading contributions. As the research portfolio evolves in time, existing research facilities are phased out as new ones are implemented. One of greatest needs is the control of a continuous high-pressure compact plasma, which will likely require a new intermediate-scale research facility in the United States to establish its feasibility. Another significant challenge is the qualification of the materials and components that surround the plasma and are exposed to fusion irradiation. One of the greatest opportunities is for the United States to take a leading role in the engineering sciences for high-critical-temperature superconductors for fusion purposes.

This national research effort aimed at low-cost fusion development not only addresses U.S. strategic interest in realizing economical fusion energy in the long term but also contributes to several national science and technology goals in high-heat flux material science, advanced nuclear science, and high-field superconducting magnets.

Based on the input received by the committee and the committee’s study, the national program should contain several program elements.

Extending the Frontier of Burning Plasma Science

The U.S. fusion program has been a key contributor to the physics basis for ITER design and operation. Participation in ITER provides the most timely and cost-effective opportunity for the U.S. to benefit from the science and technology of the burning plasma regime. In the 2020-2040 period, the U.S. program, through its domestic facilities and in collaboration with international partners, will continue playing a key role in burning plasma studies and efforts to fully exploit the capabilities of the ITER facility. Alongside ITER participation, a key program element is the development of scenarios that deliver both higher levels of fusion power gain (*i.e.* $Q > 10$) and the achievement of high-power gain at lower plasma current in ITER. The high priority placed on well diagnosed plasmas in the U.S. coupled with continued U.S. leadership in developing physics-based models will provide the U.S. with unique capabilities not only to improve the understanding of reactor-grade plasmas but also to use this understanding for improving the performance of fusion systems beyond ITER. Continued involvement in the International Tokamak Physics Activity (ITPA) and future international activities coordinating burning plasma research should remain a U.S. priority.

Sustaining High Fusion Power Density with High Plasma Confinement

The U.S. has long been a world leader in the development of high performance, steady-state-capable scenarios. The planned capabilities of DIII-D and NSTX-U will remain world-leading in developing the feasibility of high performance, fully non-inductive scenarios. This involves research establishing scenarios combining high bootstrap current fraction, compatible divertor configuration, and higher-efficiency current drive technology.

Recent advances in the U.S program, motivated by theoretical studies, point to new research elements that not only offer the U.S. distinct leadership opportunities but also potentially lead to more cost-attractive fusion systems, a central theme of this strategic plan. The U.S. program in 2020-2035 should focus on these potential breakthroughs through a program to quantify the benefits of such ideas. Early in this period, planned upgrades to DIII-D and NSTX-U should provide sufficient capability to test the basic aspects of the underlying ideas and establish the feasibility of steady-state tokamak operation with good power-handling capability. However, either substantial upgrades to these facilities and/or a new facility are needed to extend these results to burning-plasma-relevant conditions where the self-consistency of transport, stability, current drive, and compatibility with a reactor relevant boundary solution can be assessed. Note that detailed models predict that the highest performance (and hence highest power density) will be achieved with optimal shaping of the plasma (including aspect ratio, triangularity, and elongation). DIII-D and NSTX-U are well positioned to provide key information on the choice of the required parameters. The committee cannot now determine whether the research needs outlined here require an entirely new facility or an upgrade of an existing facility. The details of the next-step magnetic fusion research facility should be developed through a coordinated community process that includes consideration of multiple mission elements. However, the objective of this facility should be the establishment of the science and technology needed for uninterrupted, high-power-density plasma confinement at a compact size. The resulting upgrades or new facility should be designed, fabricated, and operated by a national team.

Power Exhaust Solutions for High-Power Density Fusion Systems

A key enabling element of any U.S. strategic plan should be the development of power exhaust solutions and materials that can handle the very high heat flux intrinsic to these systems. In the United States, DIII-D and NSTX-U have world-leading diagnostic sets and the ability to vary divertor conditions over a wide range. Additionally, ITER will offer a significant opportunity to assess boundary solutions at heat flux levels much higher than in presently available devices and that therefore should be an integral part of this plan.

However, a key aspect of projecting these solutions to devices beyond ITER is the ability to confidently predict the divertor and first wall configurations compatible with very high plasma heat and particle fluxes while preventing material contamination of the burning plasma core. Because projecting boundary solutions for future devices is quite uncertain, a key aspect of any plan going forward is to reduce the predictive uncertainties through a science-driven, model validation approach to elucidating key features of the boundary solution and identifying phenomena that are not captured properly by measurement or by simulation. Additionally, several innovations to improve the heat flux handling capability of the divertor, called "Snowflake," "Super-X," and "Small-Angle Slot" divertors and including innovative material choices (e.g., liquid metal walls) should be assessed. While each of these can be developed and tested in existing facilities, confidence in such solutions for future devices may require substantially increased capability in order to explore heat fluxes and their dissipation at the high levels and densities expected in fusion power systems. For this reason, an additional requirement of the next-step magnetic fusion research facility discussed above should be tests of advanced divertor schemes with robust power and particle handling capabilities applicable to the compact fusion pilot plant.

Large-Bore High-Temperature Superconducting Coils

Recent advances in the technology of high-critical-temperature superconductors (HTS) have the potential of reducing the cost of fusion energy and providing unique benefits for increasing the performance limits of fusion systems including very high current density, operation at much higher magnetic field, and the potential for improved maintenance, for example through jointed, demountable magnets.

In order for the U.S. program to be in a position to utilize HTS magnet technology on the timeline articulated in this strategic plan, a development program should begin as soon as possible. Early stages of this effort should focus on assessing relevant means to produce coils from the HTS conductor and possible performance degradation as the bore size is increased. The United States should consider hosting a toroidal magnet test facility similar to the Large Coil Test Facility (LCTF) that was hosted by ORNL and facilitated by an implementing agreement of the IEA-FPCC. The LCTF was a successful partnership of magnet scientists from the United States, Switzerland, Europe, and Japan and between national laboratories and industry. Just as the LCTF established the engineering science for low-temperature superconductors, like those used in ITER, this new facility would invite proposals from industries around the world and establish the engineering basis for higher-field high-temperature superconductors for fusion magnets.

Materials that Deliver High Performance and Long Lifetime

Since the economics of fusion power depend critically on the amount of time available for power production, the lifetimes of materials are a critical factor in reactor design and operation. Rapid material degradation due to plasma erosion or neutron bombardment could severely limit the benefit that could be gained from a high-power core/boundary solution. In this regard, the presence of 14 MeV neutrons and their deleterious effects are very specific to the fusion environment and therefore data quantifying such effects is sparse.

To resolve key materials challenges, two branches of research are envisioned. First, the effect of long-term exposure of plasma facing materials to divertor-like conditions needs to be understood, leading to the development and qualification of materials that meet the stringent demands of a fusion system. Second, these plasma-facing materials as well as structural materials that can maintain under high neutron fluence their critical properties, transfer properties, tensile strength, and fracture toughness, would need to be developed, tested, and qualified. The development of these materials requires a better scientific understanding of the processes that modify material properties. This understanding requires continued improvement in theory, numerical simulations, and experimental capabilities.

During the 2020-2035 period, the U.S. program should develop plans for new facilities to address these materials research needs. First, the U.S. would bring online a non-nuclear material test facility that has the capability to expose materials to relevant heat fluxes over the range of plasma conditions expected in future fusion systems. Such a facility (similar to the proposed MPEX facility) would provide a unique test bed for new materials including composites and liquid metals. Second, and later in this period, the U.S. would develop a facility and research plan leading to construction of a fusion neutron source for tests of modest-scale-sample materials and components in a 14-MeV neutron environment. This research should consider the benefit, cost, and timing of nuclear materials testing using a spallation source. A new fusion neutron source would be a world-leading scientific instrument, enabling U.S. and international researchers to explore effects not possible at any other facility and would complement the efforts of other nations that are focused on exposure of smaller material samples (for example, a beam-driven neutron source like IFMIF). Delivering the necessary capabilities in a cost-attractive manner should be a key factor in the choice of concept.

Blanket Systems that Breed Tritium and Extract High Quality Heat

A very important component of any fusion energy system will be the ability to efficiently breed and extract tritium and convert the fusion energy to high quality heat for electricity production. In particular, achieving sufficient tritium breeding and extraction efficiency is absolutely critical to the success of fusion given the very limited availability of tritium. As noted above, the worldwide fusion program has developed plans for significant technical development of blanket systems through the ITER Test Blanket Module (TBM) program and other dedicated research worldwide. The U.S. should invest sufficiently in blanket R&D to ensure that we are capable of leveraging this international investment while addressing specific issues associated with a compact fusion reactor. A decision whether or not to become a supporting participant in the TBM program would be part of a national evaluation of research options considering the time-line for the final design, licensing, and installation of TBM modules. Examples of research issues to be addressed in the national program include heat generation and removal at very high-power density and potential new blanket solutions that are predicted to achieve very high thermal efficiency and provide a path to tritium self-sufficiency.

In addition to the research elements above, the committee views other considerations as important guidance for the national strategic plan for fusion energy.

Effective Leadership and Participation in the ITER Research Program

ITER will provide the first laboratory for studying the behavior of a burning plasma, and as such will offer an unprecedented opportunity to United States fusion scientists to move into what we all acknowledge as the next frontier in our field. The U.S. fusion research community should be prepared to fully embrace that opportunity. Maintaining technical leadership is essential for that readiness, but it is just as important to optimize the organization of the ITER research program to facilitate that participation. This will eventually be decided in negotiation between the Domestic Agencies and the ITER Organization Central Team, but a USBPO Task Group has already prepared “Recommendations for ITER Experimental Operation, U.S. Team Formation and Participation” to help guide the process.

Maintaining Readiness to Move to Next Steps After ITER

The United States has not constructed a large facility since the 1990s, when Alcator C-Mod and NSTX came into operation. Several of our international partners in ITER are in the midst of a long period without a major domestic tokamak facility, and much of their expertise developed in the past has been lost through attrition. If the United States wishes to maintain scientific and technical leadership in this field, the nation needs to maintain the skills to design, construct, and operate a world-class fusion research facility. This potential for leadership should engage the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

FUSION SCIENCE PREDICTIVE MODELING AND EXASCALE COMPUTING

Fundamental to this strategic plan is the continued role of theory, simulation, and computation in motivating innovative approaches to improving the prospects of fusion energy. This encompasses research in burning plasma physics, materials science, fusion nuclear science and engineering sciences. These efforts benefit tremendously from the availability of exascale computing capabilities to tackle complex problems and high-capacity computing for scoping studies, machine learning, and data analysis. Utilizing these tools, validation of important physics models should be a strong emphasis of the R&D program supporting this plan.

The creation of the DOE Exascale Computing Project[4] in FY2017 has provided the impetus for the realization of a high-fidelity Whole Device Model (WDM) of fusion plasma applicable to a high-performance advanced tokamak regime, integrating the effects of turbulent transport, plasma collisions, and neutral particles, energetic particles, plasma-material interactions, as well as heating and current drive. At the present time, the Exascale Computing Project is one of the largest projects in the U.S. DOE Office of Science.[5] Whole device modeling holds the promise of being a powerful predictive tool for current and future fusion devices that will access hitherto unrealized plasma regimes, and has the potential to produce scientific discoveries of new and emergent behavior of burning plasmas that have been so far studied piecemeal. The project will be developed in a computational ecosystem that brings together plasma physicists with applied mathematicians, computer scientists, and other application scientists using a diverse range of software technologies and several co-design centers. The continued growth of exascale computing, which is supported by U.S. DOE/ASCR, is a valuable opportunity for United States fusion scientists and represents at the present time the largest project in the Office of Science,

PROMOTING DISCOVERY IN FUSION ENERGY SCIENCE AND ENGINEERING

To reduce risk and encourage discovery, the long-term research strategy should develop promising innovations in burning plasma science and fusion engineering science that can accelerate fusion development or improve and reduce the cost of fusion as a source of electricity. New insights and discoveries are expected to occur in all of the interconnected research in burning plasma science, materials science, fusion nuclear science, and engineering science. But the committee feels that research on less developed and therefore more speculative topics should continue to be a feature of the U.S. program. This might include some research previously provided by the ARPA-E ALPHA Program [Ref] that supports the national program leading towards a compact fusion pilot-plant. An ongoing program promoting discovery in fusion energy science would be similar to the existing U.S. DOE/FES program in Discovery Plasma Science, except any program in Discovery Fusion Science would need to be open to the possibility of intermediate scale research facilities involving multiple institutions. While some research would be supported by competitive peer review, the selection of intermediate scale facilities should follow a conceptual design effort and be guided by the evaluation of a national team of experts.

The recent FESAC report *Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy* listed several revolutionary ideas that would “dramatically increase the rate of progress toward a fusion power plant.” These breakthroughs include substantial increase in fusion performance, simplification of fusion enabling technologies, reduction in fusion system cost or time to delivery, or improvements in reliability and safety. Example transformative enabling capabilities (TEC) include: (1) advanced algorithms, like machine learning and integrated data analysis, to improve the methods to control a burning plasma and to facilitate predictive understanding from advances in exascale computing,

(2) high critical temperature superconductors, (3) new material designs, advanced fabrication methods, and additive manufacturing offering the potential for local control of material structure, and (4) novel technologies for tritium fuel cycle control. Each of these TECs presents a tremendous opportunity to accelerate fusion science and technology toward power production. Dedicated investment in these TEC areas for fusion systems is needed to capitalize on the rapid advances being made for a variety of non-fusion applications so that their transformative potential for fusion energy is fully realized.

In addition to the FESAC Report on *Transformative Enabling Capabilities*, the committee was presented with two additional examples for promising discovery in fusion energy science. These are described below.

“Hidden Symmetry” versus “Axisymmetry”

Magnetic fusion energy requires a toroidal confinement region with strong magnetic field to contain the high-pressure plasma. As described in Chapter 2, the tokamak configuration is most successful and best understood configuration for magnetic fusion energy. ITER is also a tokamak as are the two major United States research facilities, DIII-D and NSTX-U. While tokamaks use relatively small non-symmetric magnetic fields, the other configuration, called the stellarator, is strongly non-symmetric by design. The two largest stellarators are the Japanese Large Helical Device (LHD) and the German Wendelstein 7-X (W7-X) stellarator. Both of these experiments are built with superconducting magnets, and both are conducting successful ongoing investigations of the potential for uninterrupted magnetic confinement for fusion with a more complex, non-symmetric set of magnets. United States scientists are active participants in the German W7-X experiment.

The stellarator has benefitted from advances in theoretical understanding leading to improved particle confinement at high plasma temperature. This improvement is achieved through careful optimization of the shape of the magnetic field. The present day focus of the United States stellarator program creates a “hidden symmetry” of magnetic field, called the quasi-symmetric approach. A stellarator with a “hidden symmetry” has favorable single particle orbits and pressure driven currents that are similar to axisymmetric tokamak configurations. Validating the effectiveness of these optimization approaches defines a major element of the existing experimental stellarator program. Presently, the world’s only stellarator with hidden symmetry is the Helically Symmetric Experiment (HSX) located at the University of Wisconsin. While the HSX program has definitively demonstrated neoclassical confinement of thermal electrons, the small size of the HSX device has prevented the investigation of thermal and energetic ion confinement and plasma flows in quasi-symmetric magnetic systems. Because the behaviors of a plasma confined with “hidden symmetry” informs the predictive capability of all magnetic configurations, including the axisymmetric tokamak, a unique opportunity for discovery exists through exploration of a larger stellarator experiment where “hidden symmetry” can be evaluated at a device size sufficient to fully investigate confinement effectiveness and understand how plasma flow physics can positively impact turbulent transport, MHD physics and impurity confinement.

Beam-Driven Plasma Neutron Source versus Fission-Based Neutron Source

A key facility needed to prepare for initial operation of a compact fusion pilot plant is a prototypic 14 MeV fusion neutron source capable of testing fusion blanket concepts, as well as to obtain the neutron-induced degradation data required for the initial stage of pilot plant licensing. The United States fusion nuclear engineering community has long advocated a dedicated facility with a reliable steady-state plasma source for this purpose. Concerns about the costs of fusion neutron sources need to be addressed in arriving at the most fusion neutron source for cost-effective testing. Various approaches for blanket and materials testing are characterized by the useful irradiation volume and the neutron energy spectrum. Research facility options include fast fission reactor test facilities, accelerator-based ion sources, or somewhat non-prototypic neutron spectra involving spallation neutron sources. A beam-driven plasma source may provide a lower cost approach while also providing a prototypic neutron spectrum. A beam-driven plasma source consists of a relatively small magnetic confinement device that is operated continuously by injecting energetic neutral beams of deuterium and tritium atoms that generate a fusion neutron spectrum for testing. A low-cost linear mirror device, called the gas dynamic trap (GDT), as well as beam-driven tokamak or alternate plasma-based, accelerator-based, or innovative fission reactor facilities, should be evaluated to determine which may provide an innovative solution to fusion's nuclear testing needs.

Other opportunities for discovery in fusion energy science having high scientific merit and technical readiness should be promoted provided that they significantly advance burning plasma science, materials science, fusion nuclear science, or engineering science.

RESPONDING TO A UNITED STATES DECISION TO WITHDRAWN FROM THE ITER PROJECT

Chapter 3 describes the importance of burning plasma research, explains why continued participation as an ITER partner is important to United States fusion energy research, and describes how ITER participation will inform the design of a compact fusion pilot plant as a new element of the United States magnetic fusion program. The benefits of continued U.S. participation in ITER are compelling for several reasons: (1) ITER is the only existing experiment with a mission to explore burning plasma physics at the power plant scale, (2) ITER research is currently a major focus of the U.S. fusion research program, (3) the development of national expertise in burning plasma science requires the hands-on participation by experts, (4) ITER construction is more than half complete, and the first plasma experiments are expected to begin in less than ten years, and (5) as an ITER partner, the United States fully shares in the technology that will establish the feasibility of fusion while providing only a fraction of the costs. However, should the United States decide to end its participation in the ITER project, the need to address key burning plasma physics issues remains. Advancing toward a national fusion energy goal requires progress in all of the interconnected program elements needed for a low-cost demonstration of fusion electricity: burning plasma science, materials science, fusion nuclear science, and engineering science.

The committee's response to the scenario in which the U.S. is not an ITER partner is based on the scenario in which the U.S. continues participation in the ITER project. Irrespective of whether the U.S. remains an ITER partner, the committee recommends the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant at the lowest possible capital cost and the production of electricity from fusion. In this way, the committee's long-term strategic guidance is generic and applies to both scenarios.

All previous strategic plans reviewed by the committee call for construction and operation of a burning plasma experiment and the demonstration of scientific and technical feasibility prior to construction of a facility capable of electricity production. This committee concurs with this assessment. A burning plasma experiment is a critical next step toward the realization of fusion energy, and the science and technology gained from a burning plasma experiment, like ITER, will answer key questions needed to design a compact pilot-plant. The study, control, and manipulation of a burning plasma will give scientists their first opportunity to demonstrate many technical capabilities needed by an energy-producing magnetic fusion device. With access to a burning plasma experiment, scientists will have the means to answer fundamental questions pertaining to energetic alpha particles created by fusion reactions, plasma transport processes in fusion reactor conditions, methods to control of plasma transients, divertor science, and the integrated scenarios that simultaneously test the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components needed for a fusion energy source. If the United States wishes to take leadership in fusion energy development and pursue a program toward a compact pilot plant, national expertise in burning plasma science needs to be developed through hands-on operational participation and scientific study by U.S. fusion scientists.

For the scenario with the United States remaining an ITER partner, research toward the second goal of compact, attractive fusion power generation will build upon the ITER experience and focus on high power density plasmas, and the integration of core and edge physics in the regime required for a compact fusion pilot plant. However, if the United States were to withdraw from ITER, the United States would need to design and construct a larger and more ambitious research facility with a capability to explore burning plasma science with deuterium-tritium operation. The direct study of high-gain burning plasma physics and access to research opportunities necessary to evaluate long plasma duration and burning plasma control methods are central long-term goals of the United States program. As an alternative to ITER, the expanded fusion nuclear program for a high-power density burning plasma facility would be expensive for the United States to undertake without international support, and it would likely delay progress in the field. Such an expanded fusion research program, however, would be critical for directly addressing the physics of a strongly coupled burning plasma, and addressing the key challenges discussed above.

A decision by the United States to withdraw from ITER would make international collaboration far more difficult. Nevertheless, the United States would need to explore other avenues for collaboration and international cost-sharing, and important avenues for collaboration may still remain. In particular, the United States has already been engaged in the design of the China Fusion Energy Test Reactor (CFETR), and if that collaboration could be maintained, it would provide valuable insight on fusion technology. However, such collaboration, particularly in the event of a U.S. withdrawal from ITER, would require the United States to have its own vibrant fusion program with value to offer to those collaborating with the United States.

Given the resources required, the primary initial focus of a U.S. program without ITER participation would still be a high-power density burning plasma tokamak. However, the mission for this new facility would need to be expanded to include study and control of self-heated burning plasma. Design studies for such an experimental device, building on results from new experiments on DIII-D and NSTX-U, state-of-the art theory and simulation, and possibly technology innovations, would need to should begin as quickly as possible in response to a United States decision to withdraw from ITER. These design studies would need to include the licensing and facility requirements for safe handling of tritium. Once constructed, this new facility would give United States fusion scientists the necessary means to study burning plasma science and technology and to maintain progress toward the long-term development of commercial fusion power.

SUSTAINING THE NATIONAL PROGRAM

The demonstration of fusion electricity is a long-term undertaking, requiring progress at both national and international levels and sustained support. Besides the scientific and technical challenges to continued progress, fusion energy research needs solid support from the broad scientific community and throughout the political system. The 2009 NRC report *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program* recommended that steps should be taken to “seek greater U.S. funding stability for the international ITER project to ensure that the United States remains able to influence the developing ITER research program, to capitalize on research at ITER to help achieve U.S. fusion energy goals, to participate in obtaining important scientific results on burning plasmas from ITER, and to be an effective participant in and beneficiary of future international scientific collaborations.”

The first half of the committee’s recommendations is continued participation in the ITER project as the nation’s primary experimental burning plasma component within a balanced long-term strategic plan for fusion. The committee concurs with the conclusion from the Secretary of Energy’s Report to Congress in May 2016, “ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power.” The studies carried out with ITER will inform accompanying research and technology programs needed to progress beyond ITER to a commercial fusion reactor.

The second half of the committee's recommendations recognizes that if the United States is to profit from its share of the ITER investment, the nation's strategic plan for fusion should combine its ITER experience with the additional research needed to realize fusion. In addition to burning plasma science, the interconnected research in materials science, fusion nuclear science, and engineering science should be expanded. Without this additional research, the United States risks being overtaken by other nations as they advance the science and technology required to deliver a new and important source of energy.

BUDGET IMPLICATIONS

The committee was asked to consider the budget implications of its guidance. Estimates were examined for the cost and schedule for the two main research activities: (1) construction and operation of the ITER burning plasma experiment and (2) a national program of accompanying research and development leading to the construction of a compact fusion pilot plant. The committee also examined the schedule and budget implications of a decision by the United States to withdraw from the ITER project. Because the committee's long-term strategic guidance covered the next several decades, all cost and schedule estimates are necessarily approximate. Implementation of the committee's strategic guidance will require significant planning and thought by the fusion research community, involvement with international partners, and oversight by the U.S. Department of Energy. Additionally, because the committee's strategic plan involves research and technology development over several decades, the impact of unanticipated discoveries, breakthroughs, or technical setbacks that would influence the schedule and cost of the strategic plan could not be determined.

With the baseline cost and schedule for U.S. contributions to ITER's first plasma subproject now formalized, the committee's recommendations imply a sustained national funding for more than two decades at a level that is about $200 million higher than the presently enacted funding levels. About half of this additional amount is required to meet ITER commitments and the other half is needed to launch the science and technology supporting the research leading to a compact fusion pilot plant. Appendix H summarizes the input used by the committee in its considerations of the budget implications of its recommended strategic plan for U.S. burning plasma research.

Based on information received, including the Updated Long-Term Schedule for ITER, the 2016 DOE Report to Congress,[6] and the 2017 DOE, Project Execution Plan for U.S. ITER Subproject-1,[7] continued U.S. participation in the ITER project requires additional annual funding near $100 million, representing half of the required incremental funding.

The start of a national program of accompanying science and technology leading a compact pilot plant at the lowest possible capital cost will also require additional funds of $100 million annually, representing the other half of the required incremental funding. This estimate is based on recent reports of the U.S. DOE FESAC, including 2014 Report of the subcommittee for Priorities Assessment and Budget Scenarios,[8] the 2013 Report of the subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science,[9] and the 2013 Report of the subcommittee on the Priorities of the Magnetic Fusion Energy Science Program.[10] All of these reports recommended additional funding to address the full range of scientific, technical, and engineering challenges for fusion energy. They also recommended an evolution of the research portfolio as existing research facilities are phased out and new ones are implemented.

Programmatic decisions for new facilities and programs mentioned in this report should be based on cost-benefit analysis and technical input from the U.S. fusion research community as recommended in Chapter 6. If the required engineering and science studies begin soon, new world-class research facilities could be available to enable resolution of the critical issues needed to finalize the design and begin construction of a compact fusion pilot plant having the lowest possible capital cost. Such a program with a cost-attractive goal for the demonstration of fusion electricity would also provide important scientific opportunities for U.S. researchers and U.S. industry and deliver technical know-how to the nation's effort to provide abundant fusion power.

In summary, based on information received and described in Appendix H, including the updated long-term schedule for ITER participation and previous strategic planning efforts of the U.S. DOE FESAC, the committee expects the implementation of its recommendations, including both continued participation in ITER and the start of a national research program for a compact pilot plant, to require an annual funding level about $200 million larger than presently enacted levels, about half required to meet ITER commitments and half needed to launch the science and technology supporting the research leading to a compact fusion pilot plant. This funding would need to be sustained for several decades.

NOTES

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Comments on Organizational Structure and Program Balance

Implementation of the recommended strategic plan for United States magnetic fusion energy research will require an expanded organizational structure for the U.S. DOE Office of Fusion Energy Sciences (OFES) with more deliberate planning, regular opportunities for input from the research communities, coordination of research efforts in burning plasma science, materials science, fusion nuclear science and technology, and the engineering sciences needed to realize an economical pathway to fusion electricity for the nation.

Three primary organizational and program changes are described below: (1) a new division within the U.S. DOE Office of Fusion Energy Sciences, (2) adoption of a long-range strategic plan, and (3) strong engagement from the fusion energy science research community. The expanded organizational and program management structure within the OFES is needed to emphasize burning plasma science in preparation of ITER studies and to coordinate the research and technology within a growing national program that looks beyond ITER. Importantly, this structure enables the comprehensive, long-range plan that is needed to carry out the accompanying research aimed at a low-cost, compact fusion pilot plant. This includes support for the fusion technologies that will enable a compact, low-cost pathway to fusion demonstration and strengthening communication with the multi-disciplinary research communities.

Comments are also made regarding (1) safety and licensing standards for fusion energy research facilities, (2) the health of the U.S. fusion research program, (3) the importance of continued participation in the larger international effort, (4) the need to encourage growth of private sector capabilities in fusion energy technology, (5) the value of cross-disciplinary partnerships in related science and technology efforts, and (6) the importance of public outreach to better communicate the long-term potential for economical fusion energy and to better engage students and educational institutions in the integrated science, technology, engineering, and mathematics at the foundation of fusion energy science.

This chapter concludes with six findings and seven recommendations aimed to guide the implementation of an expanded U.S. DOE FES research program and strengthen community participation in the burning plasma science, materials science, fusion nuclear sciences, and engineering sciences needed to realize an economical pathway to fusion electricity for the nation

ORGANIZATIONAL STRUCTURE AND PROGRAM MANAGEMENT

The pathway ahead for fusion development requires augmentation of ongoing burning plasma research with the technology and engineering research required to enable fusion power systems. As discussed in Chapter 2, in the last ten years, many of the complex physical processes of magnetically confined plasma have become understood, and there is growing confidence in the predictions of validated computer simulations and models for burning plasma performance and in the promising new technologies that have the potential for lower-cost approaches to fusion energy. As was also discussed in Chapters 4 and 5, the pathway ahead for fusion development requires augmentation of ongoing burning plasma research with the technology and engineering research required to enable fusion power systems. The demonstration of fusion electricity production will require continued innovations in the technology and engineering needed to sustain the plasma, manage the power exhaust, and take advantage of new technologies to breed tritium fuel and realize innovative approaches to reduce the size of the fusion pilot plant. Progress calls for management and coordination of a multi-disciplinary effort to promote continued innovations in those technologies that will reduce the cost of the fusion development path and to further develop the knowledge, expertise and infrastructure needed to design a compact fusion pilot plant.

Expanding the OFES Organization to Meet Program Needs

The current organizational structure for the U.S. DOE Office of Fusion Energy Science (OFES) has been adequate to advance to the burning plasma, but is not well suited to accommodate the larger scope**.** Currently, two divisions exist in OFES: “Research” and “Facilities, Operations, and Projects.” The first has been a generator of ideas and exploration to assess the viability of different magnetic confinement configurations, plasma behavior and characteristics needed for sustained fusion. The second division attends to the oversight of existing projects. However, the committee finds that the current structure is not readily adaptable to the expanded science scope and integration of the required sophisticated technologies.

To achieve the necessary focus and coordination, the committee proposes strengthening the organizational structure of the U.S. DOE OFES program to better focus on the two goals of the long-term strategy. As discussed in Chapter 3, data and modeling/simulation associated with ITER experiments will provide critical information to design the future pilot plant. Thus, the research division should be re-organized with an explicit focus on burning plasma research as a centerpiece of the division. As noted in Chapter 4, a new fusion technologies division should be added to manage and organize research leading to technologies required to improve and fully enable the fusion power system. Effective coordination between the research, technology, and facilities divisions should be strongly emphasized by U.S. DOE/FES leadership.

The goal of this new division would be to manage a portfolio of research tasks including engineering studies of the compact fusion pilot plant that can guide and prioritize research needed to fully establish the science and technology of the fusion power system. The purview of the subgroups within the new U.S. DOE OFES division should include, for example, high-temperature superconducting (HTS) magnets, structural materials, blanket, and tritium technologies. The revised organizational structure will facilitate both technical innovation and coordination on interrelated elements within and between FES divisions.

Ultimately, the realization of fusion energy as a source of electricity will involve the design and construction of complex facilities that rely upon continued development of the underlying enabling technologies. Past research facilities for fusion energy science illustrate the significant boosts in capability that result from state-of-the-art advancement of enabling technology. For example, advancement in glass forming technologies were essential for the National Ignition Facility (NIF). Migration of inclusions from the crucibles into the glass had to be overcome, and continuous glass forming techniques had to be developed in order to supply the quantity of high-quality optical glass needed. Similarly, advances in the manufacturing of large niobium-tin (Nb_3Sn) superconductors, as discussed in Chapter 2, were essential to the success of the ITER facility and will result in the world’s largest superconducting magnet system.

Looking to the future, continued developments in the underlying enabling technologies are necessary and should be supported. For instance, superconducting magnet technology that can operate at even higher magnetic fields than possible with Nb_3Sn conductor will be critical for compact and lower-cost fusion power plants. New manufacturing methods are now able to fabricate complex material structures that may result in extremely beneficial thermal and mechanical properties for fusion applications. Similarly, it is not hard to imagine that materials research is also needed to develop a tritium-breeding blanket in the wall facing the burning plasma.

In short, many transformative and innovative technologies listed in the 2018 report from the FESAC Subcommittee on Transformative Enabling Capabilities[1] may significantly improve the economics of fusion power systems. Strengthened program support within the U.S. DOE OFES is needed to support the science and engineering that will lead to the technological leaps necessary for a fusion machine.

Adopting a Long-term Strategy Toward a Fusion Energy Goal

The United States fusion energy science program needs a long-term strategy that ensures balanced growth and integration, supporting a diversity of program elements that are inherently interlinked through the national fusion energy goal.

Implementation of the strategic expansion recommended in this report will result in a research program that combines burning plasma science, materials science, fusion nuclear science, and the engineering science needed for guiding, designing and ultimately constructing a compact pilot plant and generating electricity from fusion. The resulting research program in the United States begins with a current focus on burning plasma science and adds research elements that will fully enable a fusion power system. These include engineering of high-field superconducting magnets, fusion nuclear science and the related technologies needed for the components surrounding a burning plasma and, notably, the fusion "blanket" that can breed tritium fuel and the materials science needed to engineer the structures that can withstand the magnetic forces and neutron irradiation in magnetic fusion energy.

With any burning plasma effort, and especially with the multi-national ITER, the shift to "big science" at the international scale along with national facilities with specific and focused research missions have implications for all areas of the U.S. fusion research community. As noted in the 2004 report of the NAS Burning Plasma Assessment Committee,[2] as the U.S. fusion community enters the burning plasma era and ITER operation begins, the scale of even the largest national research facilities effectively become "smaller-scale" programs having specific objectives that will be complementary to ITER. During the next decades, research facilities will continue the trend toward national facilities that, although are smaller than ITER, still addressing essential research tasks in the most cost-effective manner.

The committee's strategy to realize a fusion plant will require new U.S. research facilities. In fact, the experience in the design, construction and successful operation of major research facilities in the United States will be critical in both the science mission and in establishing and maintaining global leadership. Successful and efficient completion of new major facilities requires institutional knowledge in the form of experienced scientists and engineers, and cannot be achieved solely by relying on theory or by reading research articles about facilities in other countries. The adoption of a new strategy for U.S. fusion energy research will necessitate an evolution of major research facilities. These facilities should continue to be world-class and serve the national fusion research community to develop scientific and technical leadership in fusion energy science.

In a well-managed strategy, research priorities would be expected to evolve over time as research questions are answered and tasks are completed, laying the foundation for each new stage. The retirement of facilities that have served their intended purpose and the planning for new machines that will replace them should follow priorities established through a formal structure that includes community-based program reviews and strategic planning. The contributors from university and U.S. DOE and industry research labs will give voice to the advances and challenges in their respective institutions that together will inform major decisions as well as the direction of the program more broadly.

Strengthening Community Organization and Input

An expansion in the U.S. DOE OFES to support fusion science and technology beyond the burning plasma science will require coordination among multiple research communities and may include scientific experts from U.S. industry and utilities. The current MFE community is largely rooted in academic institutions, with key groups and facilities in nationally funded laboratories, with a growing international involvement through participation in ITER and collaboration on other international facilities. This diverse nature is different in character than, for example, Inertial Confinement Fusion, which is mission-driven by the national laboratories responsible for stockpile stewardship. While there are many able contributors, the expanded research community is only beginning to be unified in the greater vision.

To ensure incorporation of innovations and discoveries while making consistent progress toward the long-range fusion energy vision, the committee recommends changes to strengthen community engagement.

The current management structure of the Office of Science allows for input from the research community through advisory boards. These advisory boards are subject to the Federal Advisory Committee Act (FACA) rules, which require providing the public with the opportunity to participate in board meetings, where recommendations are discussed. Each advisory board is composed of approximately twenty individuals, selected for their expertise in the different areas critical to scientific and technical growth and management, including relevant university and laboratory personnel.

The Fusion Energy Sciences Advisory Committee (FESAC) is the advisory board for the OFES, and according to its charter, meets and acts only when specifically tasked by the Office of Science to provide advice. FACA rules dictate that FESAC restrict advisory comments to those directly responsive to specific committee charges.

To achieve consistent long-range planning through the FESAC, the committee examined the practices of other advisory committees within the Office of Science to identify those that may serve as a model for OFES. For the U.S. DOE Office of Science High Energy Physics Advisory Panel (HEPAP), a subcommittee called the “Particle Physics Project Prioritization Panel” (P5), was charged with making recommendations on priorities of large facility projects, considering their projected costs. The first P5 report, issued in October 2003, described their role as the “guardian of the facilities roadmap.” P5 is convened approximately every five years, including 2008 and 2013, to provide “long-range planning for a 10-year, and 20-year global vision.” For HEPAP, the process of soliciting input from the community works fairly well because P5 prioritization takes that input into account along with fiscal constraints and the need to balance large and medium size projects. HEPAP has the clear and explicit commitment of the Office of High Energy Physics that the recommended priorities will be honored in funding decisions.

The committee recommends that the U.S. DOE/FES ensure the long-range U.S. strategic plan is developed, regularly updated, and vetted by the community through a P5-like process that covers the domestic and international facilities/programs. This effort should engage the professional societies supporting the science and technology for fusion energy, including the American Physical Society Division of Plasma Physics (APS-DPP) and the American Nuclear Society Fusion Energy Division (ANS-FED). In addition, defined events held at regular intervals will bring the U.S. magnetic fusion energy research community together to build a unified national program.

The committee also finds that the magnetic fusion energy research community, itself, needs to develop a culture that provides for broad, transparent input to the national program. Self-organized community workshops, or cross discipline community meetings organized by professional societies, can provide important forums to vet ideas and should be encouraged by the leadership.

A recent successful example of magnetic fusion energy research community engagement is the pair of workshops held in Madison and Austin in 2017 that enabled a long-overdue discussion among members of the plasma science community about collective research priorities and potential pathways to fusion energy. The workshops, organized by the grassroots U.S. Magnetic Fusion Research Strategic Directions[3] program committee, were well received by those who participated, and they contributed to the development of a shared vision of the field, although they lacked representation from some disciplines that will be critical to the development of fusion power plants. A strong consensus emerged from the workshops that the science of magnetically confined plasmas has advanced sufficiently that a broadened national effort encompassing the science of fusion energy technologies in addition to burning plasma science is now appropriate.

Another example in this electronic age, is the online forum that was established[4] by a self-organized group of “Early Career Fusion Scientists” (ECFS) that took inspiration from the workshops. A poll conducted of the ECFS participants by the group’s leaders shows that group members are strongly motivated in their work by the prospect of fusion energy, and they have expressed enthusiasm for a strategic plan that would unite the community around a roadmap to achieve fusion-based electricity within their lifetimes.

In summary, meaningful coordination and alignment should occur regularly through such activities as FESAC charges to solicit a long-range plan on program/facility priorities and future workshops with significantly broadened participation to include all fields contributing to fusion technology. These activities, coupled with the creation of a new division, are recommended to bring together the creative talent and the management needed for a unified national effort. Together, they should represent the community and enable a prioritization of resources in the most equitable way possible to ensure a vibrant national program.

FURTHER STRENGTHENING OF UNITED STATES FUSION RESEARCH

In addition to the primary management guidance above, the committee also comments on six additional areas: (1) safety and licensing standards for fusion energy research facilities, (2) the health of the U.S. fusion research program, (3) the importance of continued participation in the larger international effort, (4) the need to encourage growth of private sector capabilities in fusion energy technology, (5) the value of cross-disciplinary partnerships in related science and technology efforts, and (6) the importance of public outreach to better communicate the long-term potential for economical fusion energy and to better engage students and educational institutions in the integrated science, technology, engineering, and mathematics at the foundation of fusion energy science.

Setting Safety and Licensing Standards for Fusion Energy Research Facilities

The pathway toward a compact fusion pilot plant requires one or more research facilities that are capable of safely handling tritium and fusion neutrons, as well as other recognized fusion hazards such as neutron-activated materials, high magnetic fields and significant thermal, mechanical loads. Siting and licensing strategies for such facilities should be developed well in advance so as not to delay the progress toward the compact fusion pilot plant. It is reasonable to expect that these tritium-capable fusion nuclear research facilities will be owned by the U.S. DOE and sited at one or more national laboratory. The operation of these facilities under U.S. DOE auspices will be an opportunity to provide insight toward future siting and licensing of a compact fusion pilot plant.

The U.S. DOE Fusion Safety Standards[5,6,7] were developed in the 1990's during the ITER Engineering Design Activity[8] in preparation for a potential siting of ITER in the United States. Development of such standards required a multi-year effort with tight collaboration between the main stakeholders, including U.S. DOE, the U.S. Nuclear Regulatory Commission (NRC), national laboratories, and industry. The U.S. DOE Fusion Safety Standards were developed with the intention that that they would provide an initial set of requirements and design guidance that could later be used by NRC to develop a fusion regulatory framework for commercial fusion.

Health of the U.S. Fusion Program

As was stated in the 2004 NRC Burning Plasma Assessment report (p. 119),[9]

> The well-trained fusion scientist or engineer of the coming decades will require knowledge of concepts and techniques that do not now exist. The hardware and techniques for engineering and scientific research can be expected to change in fundamental ways. Examples involve expected advances in computational techniques, laser and other radiation sources for probing plasmas, sensors, measurement techniques, materials, manufacturing techniques, and so on. Furthermore, many of the scientific concepts used to describe physical phenomena will be qualitatively more sophisticated a decade or two hence. Examples of areas currently undergoing dramatic changes include the modeling of nonlinear processes ranging from plasma heating to magnetic reconnection and models of plasma turbulence and turbulent transport. These and many other

> areas are likely to change dramatically in the decades of the burning plasma experiment. Thus, the basic training of fusion scientists and engineers in broad areas of physical science and engineering must continue to be an integral part of the fusion program.

The committee has taken notice of the enthusiasm within the United States fusion science research community as reflected in the strategic workshops that reported on outstanding recent scientific and engineering progress and an eagerness of early career fusion scientists and engineers to help realize fusion as an energy source. Nevertheless, there is concern that the future health of the United States fusion energy sciences program is uncertain. This concern stems from shutting down major experimental facilities (e.g., Alcator C-Mod) and smaller university scale experiments without replacements. This domestic program contraction may be contrasted with new medium and large-scale facilities in Europe and Asia (W7-X, MAST-U, JT60-SA, KSTAR, EAST, WEST, HL-2M,). The many contributions from United States researchers show a history of innovation. The quality of United States research has allowed the nation to remain, until now, a respected peer in the international fusion community. In the future, maintaining a leadership role will require new domestic research facilities that target key questions and a demographically balanced workforce. Furthermore, even though there is widespread community support for ITER, the United States has yet to prove that it can be a reliable ITER partner, and further delays are likely if the nation does not fulfill its commitments on schedule.

A 2017 white paper on the status of university-based fusion science research submitted by the University Fusion Association (UFA)[10] expressed concern that reductions in federal funding for magnetic fusion research at universities, and specifically a contraction in the number of experiments, lead directly to reductions in the training of graduate students. It is further argued that these cutbacks also accelerate the loss of research infrastructure and lead to reticence for university departments to hire new faculty with expertise in this area. Similar concerns were expressed in the 2004 report of the NAS Burning Plasma Assessment Committee[11] about the aging of the fusion and plasma science workforce at universities and large fusion facilities; this has been further exacerbated in the years since. The UFA survey results show that the average age of university faculty in the field has increased from 52.7 to 56 in the past 12 years, and up to 30% of current faculty anticipate retirement in the next five years.

The committee expects that the expansion of scope of OFES recommended in this report will energize university fusion research in several ways. New research initiatives to establish the science basis of fusion energy technology will create opportunities for university innovation, for stable funding to sustain university programs and to inspire the next generation of talented students to become part of the national team. Over the past decades, universities within the United States have, alongside federally funded laboratories, made innovations that advanced magnetic fusion energy plasma science and technology, leading to international recognition of U.S. leadership in the field. In the previous research era when magnetic confinement concepts were evaluated, many universities were able to contribute with moderately sized experimental facilities on site. The practicalities of burning plasma research introduce new constraints on university participation. Future construction of domestic fusion nuclear facilities involving burning plasmas and the safe handling of tritium will be sited at federally funded labs due to their larger scale and required specialized safety infrastructure. A unified research effort will require an organizational structure that enables involvement of both lab and university personnel in the use and operations of major national facilities. Planning of operations for both national U.S. research facilities and the large international facilities and ITER will require careful consideration to ensure representation and inclusion of contributing groups and broad participation of laboratory and university personnel based at off-site institutions. One approach would be for U.S. DOE to provide travel and organizational support for each facility to hold regularly scheduled “collaboration meetings” involving all participants for this purpose. Large high energy physics experiments such as those at the LHC may serve as an example for inclusive science organizational practices. In addition, the committee notes the value of university scale machines, both for their advantages in cost-effective investigation of focused research questions and for their hands-on educational value.

International Partnerships

When construction is complete, ITER will be the world's largest research facility and the most significant near-term opportunity for the United States to advance burning plasma science. ITER construction is now more than halfway completed, and the potential benefits to the U.S. of continued funded participation as an ITER partner are evident. ITER addresses questions about burning plasma science and reactor scale confinement that are essential to progressing toward the goal of fusion power. International collaboration on ITER is a means for the U.S. to gain answers to these questions as an engaged partner while sharing costs with other participants. Moreover, the standing of the U.S. in the global fusion community will hinge on fulfillment of its construction commitment as an ITER partner and also the critical engagement of U.S. researchers in support of ITER experiments.[12]

National benefits as a reliable ITER partner include future opportunities for mutually beneficial international collaborations to make advances in other aspects of the science and technology leading to fusion as an electricity source, including entertaining partnerships on future experiments sited in the United States. As already mentioned, a decision by the United States to withdraw from the ITER partnership would make international collaboration more difficult. Nevertheless, if the United States withdraws from ITER, the U.S. would still need to pursue other avenues for collaboration and international cost-sharing.

Private Sector

As major new technologies develop and mature, the division of activities between universities, government-funded labs and the private sector evolves. Considerable development often takes place in universities and national laboratories before commercial enterprise takes off. This is depicted in Figure 6.1 as developed by the 2017 Annual Report of the State of U.S. DOE National Laboratories.[13] Magnetic fusion energy research is currently in the second stage of technology maturation, called "development." During the "development" stage, a relatively small fraction of current activity is in the private sector. That proportion will grow in the coming decades, presenting opportunities both to leverage commercial ventures in technology development, and to begin preparation for a future fusion power industry.

Since the last burning plasma study in 2004, there has been a substantial increase in private sector fusion energy funding and research. This increase has been of several sorts. First there are the industrial contracts from the DOE issued to privately held corporations. This is not a new development. The most significant activity is the General Atomics (GA) contract to manage the DIII-D facility. More importantly perhaps, is that private industry is playing a major role in the construction of United States in-kind contributions to ITER. For example, GA is assembling and testing the central solenoid electromagnets. This industrial component of ongoing burning plasma science is significant and will become increasingly important as the U.S. effort progresses toward the construction of a fusion pilot plant. The expertise, developed for the ITER central solenoid in assembling large electromagnets will expand to include producing very high magnetic fields using rare earth barium copper oxide, or REBCO, superconducting cables

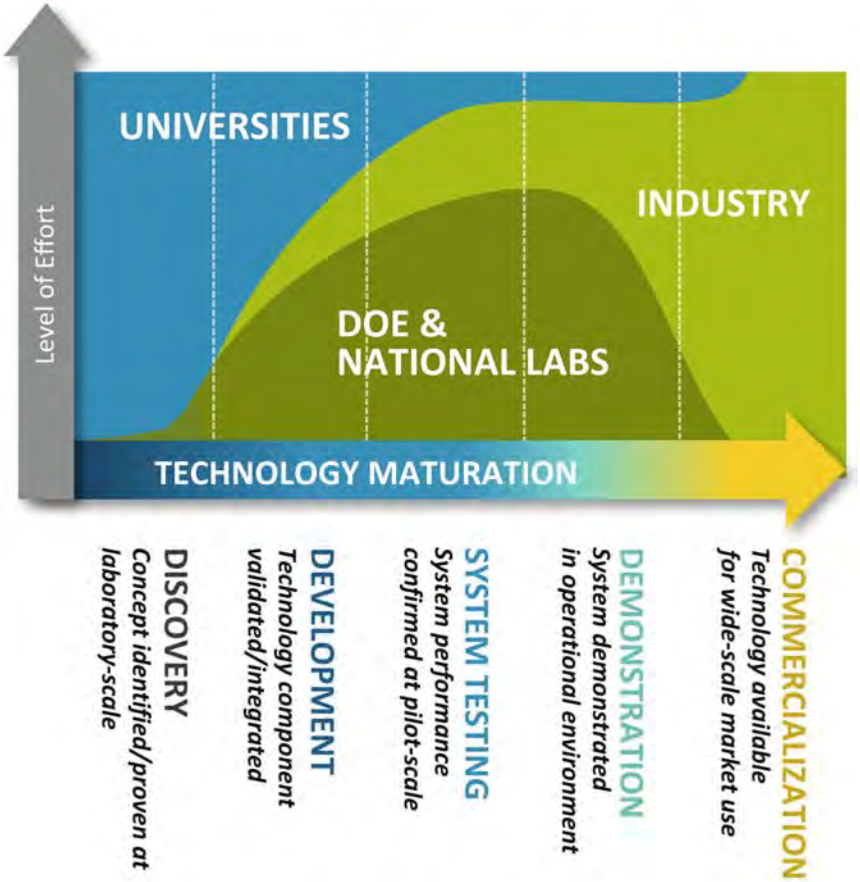

FIGURE 6.1 The institutional balance of science and technology research evolves with maturity and technical readiness of the technology. While there are areas of overlap, universities emphasize early discovery and tend to focus on research associated with individuals or small groups of faculty members. Companies respond to market needs and typically focus their R&D on near-term solutions or the integration of multiple technologies. National Laboratories have a particular capability to tackle multidisciplinary problems with long time horizons, often coupling fundamental discovery research, technology development, and demonstration projects. From the 2017 *Annual Report on the State of DOE National Laboratories*.

Fusion science and technology research are also pursued in the private sector, both nationally and internationally. The Fusion Industry Association[14] is an international coalition of companies working to develop fusion power technologies for the production of electricity. At the present time, the Fusion Industry Association has sixteen members and five affiliate members. Similar to the professional societies that represent the fusion research community (e.g., the APS Division of Plasma Physics and the ANS Fusion Energy Division), industry associations, like the Fusion Industry Association, can provide important input to implementation of the national fusion research strategy.

One privately funded fusion energy ventures is TAE Technologies, with headquarters in Foothill Range, CA. TAE Technologies was started nearly two decades ago by University of California-Irvine physics professor Norman Rostoker. In contrast to mainstream fusion research, TAE concentrates on an alternative magnetic confinement geometry, the field-reversed configuration (FRC). Though FRC confinement performance has not achieved that of tokamaks, the configuration has many attractive engineering features, including simplified divertor geometry and access for maintenance. A new medium-scale FRC experiment, dubbed “Norman” in Rostoker’s honor, was recently constructed and began operation in a single year. A predecessor device achieved confinement that is superior to previous FRC experiments.[15,16]

The recently announced Commonwealth Fusion Systems,[17] with headquarters in Cambridge, MA, is another privately funded venture. Their goal is to combine proven tokamak physics developed in decades of government-funded fusion research with high temperature superconducting (HTS) magnet technology to accelerate the path to commercial fusion energy. MIT scientists and engineers are key partners in the Commonwealth effort. Their first technical milestone is successful construction of an HTS fusion magnet, with proposed construction of a compact fusion research device able to explore burning plasma science should that technology development succeed.

All of these companies benefit enormously from the decades of U.S. Government sponsored research that led to their emergence and now train their workforce, and the fundamental research activities that remain critical before commercialization of fusion takes place. The next phase of commercialization in the United States might take a path similar to those in (1) the space industry with the emergence of SpaceX, Blue-Horizon and Virgin Galactic, and (2) in the nuclear power industry with a substantial entry of smaller, modular advanced fission concepts. The development of fusion power will require increasing participation by private industry, and, in select areas of technology, private industry is now ready to take a larger role.

Mutually beneficial partnerships can maximize information exchange between the public and private sectors by providing tools developed through U.S. DOE/FES funding to aid industry development and design, integrating tools from both sectors to provide more complete physics/engineering descriptions, and setting up the framework for each sector to propose and carry out experiments on the other sector's devices to optimize progress toward development goals. Examples might include

- Parallel private and government supported R&D on REBCO magnets, with companies and research labs contributing complementary strengths
- U.S. DOE could provide access for future private sector development experiments at facilities with safety measures and licensing for tritium and neutrons. Similar cooperative developments are now in place at Idaho National Labs, Oak Ridge and Savannah River.
- U.S. DOE/FES could provide access and support for the use of simulation and design codes, developed with Federal R&D support, to be used by the private sector within the United States to make most effective these important private sector ventures.
- There may be opportunities for U.S. DOE supported efforts to operate and exploit the science (diagnostics) on future private venture burning plasma machines.

Relationship Between Private Sector and National Goals

The U.S. fusion community, through a series of workshops and white papers, has concluded that after over a half-century of plasma physics research, sufficient progress has been made that it is now time to increase attention to engineering and technology-based development. The NAS Panel supports this conclusion. Increased industrial involvement in fusion development underscores this transition as well, and this welcome step offers the opportunity for the U.S. DOE fusion program to contribute in the form of partnerships and collaborations with industrial projects wherever appropriate. Specific contributions can be made in the form of access to high quality simulation tools as well as to special purpose experimental facilities. Intellectual property issues, while important but cumbersome, need to be resolved by mutual negotiations.

The overall conclusion is that increased industrial interest in fusion is a good sign, indicating the readiness to transition to more of a fusion energy focus and to take advantage of new opportunities for collaboration.

Linkages to Other Science and Technology Disciplines

Fusion energy science research is interdisciplinary and has resulted in technological and scientific achievements that touch many aspects of everyday life and lead to new insights in related fields such as optics, fluid mechanics, and astrophysics. Fusion research has a long history of "spin-offs" contributing to an impressive assortment of science and technology fields.[18] Strong linkages between fusion energy science and related research areas is anticipated in the burning plasma era. Several examples are highlighted below.

Exascale Computing

For several decades, fusion research has been an important driver for using high-performance computing to describe complex physical systems. Already in 1974, it was realized that simulating the behavior of a fusion plasma required a computer center dedicated to this purpose. This led to the founding of the Controlled Thermonuclear Research Computer Center as the first unclassified supercomputer center in the U.S. Its name was later changed to the National Energy Research Supercomputer Center (NERSC), and its mission was expanded to provide computing services to all of the programs funded by the DOE Office of Energy Research (now the Office of Science). Now, fusion simulation codes are being prepared for use on future exascale supercomputers (expected to become available within the next few years), capable of at least a billion billion calculations per second. In the context of the DOE Exascale Computing Project, efforts are underway to create a high-fidelity whole-device model of a magnetically confined fusion plasma. The long-term goal is to reproduce essential aspects of fusion experiments on a supercomputer, guiding the interpretation of existing experiments and helping to optimize the design of future devices, including, in particular, a pilot plant. To this end, many physical processes, involving a wide range of space and time scales, would need to be described in a way that accounts for their mutual interactions. Fusion research shares this challenge with many other scientific domains, from materials research to weather prediction, and contributes significantly to the development of a predictive computational science, with broad applicability.

Magnets

The prospect of high magnetic field strengths of 20 Tesla and above drive the development, including private sector ventures, of magnet coils manufactured from high-temperature superconductors (HTS). The technological leap to large HTS electromagnets now appears within reach, and their higher magnetic fields will enable more compact fusion machines than what is possible even when current niobium-titanium (NbTi) and niobium-tin (Nb_3Sn) technologies have reached their practical performance limits. While plasma confinement in MFE systems is currently a major driver for HTS magnet development, high field electromagnets would be transformative in other fields as well, including particle accelerators for high energy physics, MRI for medical imaging and NMR (spectroscopic method used, for example, to determine the structure of organic compounds), all of which rely on high magnetic field strengths.

Materials

One technological area which will significantly influence the design of the pilot plant is advanced materials. Both fusion and fission applications require materials to sustain high heat and neutron flux. The ability to design and tailor material and component properties is now possible with material synthesis and characterization techniques. For instance, precision control of processes enables the creation of new alloys or nanostructured material to achieve desirable properties, such as high thermal conductivity or tritium retention. One example is the research and development on silicon carbide composites, which has produced an engineered material composed of silicon carbide fibers embedded in a silicon carbide matrix to form a strong fracture resistant material that is able to withstand high displacements per atom. These advanced materials will be critical to realizing efficient fusion and fission devices.

Low Temperature Plasma Science

For the most part, laboratory plasmas for a wide variety of practical applications operate in a vastly different regime from those approaching the burning plasma state. Some naturally occurring plasmas can, along with technological plasmas, also be described as “low-temperature” plasmas, to contrast them with their much hotter magnetically confined cousins in fusion experiments. There is, however, an intersection between the two subdisciplines in the exhaust region of tokamaks and other magnetic confinement devices, known as the divertor. The divertor region of a fusion system is rich in low temperature plasma physics, with a high temperature plasma and a solid surface in close proximity. Understanding and manipulating the interactions between the low temperature plasma, neutral gas and radiation in the divertor as a means of protecting reactor surfaces from the huge exhaust heat flux produced by burning plasmas will certainly lead to synergies with studies of low-temperature and technological plasmas. Neutral beam systems developed for heating of tokamak plasma, including ITER, are another area of overlap between the MFE and low-temperature plasma communities.

Robotics and Automation

A fusion reactor is perhaps the ultimate challenging environment for essential operation and maintenance, with the surrounding components characterized by high temperature, near 500 °K, vacuum, liquid metals, confined spaces and kGy/hour neutron radiation. Remote maintenance (RM) will be a fusion power plant “device defining driver” whether the reactor is a large conventional aspect ratio design like the EU DEMO or a high-performance design like the compact pilot plant. Remote maintenance concepts should be integral to the design, construction, inspection, maintenance, operation and decommissioning of the power plant and included in assessing the costs of material and waste flow through the plant. The robotics solutions developed for fusion will have wide applicability in many other sectors, essentially anywhere that robotics solutions are required because person-entry is either impossible or highly undesirable. This includes the space sector, the petrochemical industry where there is high risk of explosion, and broader nuclear applications, especially in decommissioning fission reactors. Beyond the direct application of robots developed for fusion, there is also considerable synergy between the sensors and control systems of robotics developed for fusion and other sectors. As an example of this, the sensors and control systems developed for autonomous vehicles have been applied on the remote maintenance system in JET in the EU.

Plasma Astrophysics

Burning plasma and natural plasma research are mutually beneficial. As fusion plasmas become hotter, they more closely approach the very low levels of collisionality characteristic of many astrophysical plasmas. The process of magnetic reconnection, where rearrangement of the magnetic field impulsively releases a burst of energy, occurs in both settings. Instabilities driven by relativistic electrons and super-thermal ions have similar underlying physics. Models that describe particle and energy transport by fluctuating electric and magnetic fields are applicable in both settings. Through systematic variations of parameters that cannot be controlled in natural settings, laboratory experiments advance understanding in both disciplines. An example of this synergy is the Max Planck/Princeton Center on Plasma Physics, which is a collaborative study on processes in astrophysical and fusion plasmas.

Public outreach

Public awareness is a critical element in maintaining support for the fusion effort and associated expenditures, and for inspiring young students to consider pursuing careers in fusion energy. A systematic communication and education campaign to engage the public should be maintained and expanded, with leadership by the U.S. DOE in collaboration with the National Academies as well as professional societies such as APS, ANS, and IEEE. A solid basis for such an effort is already in place: for example, the U.S. DOE Office of Science maintains a website with tutorial materials and frequent press releases describing recent advances. The national labs have also been successful in promoting fusion energy research at their respective institutions.

Future outreach initiatives should emphasize that realizing fusion as an energy source is a united effort with contributions from many sectors across the country and through international collaborations, and from many disciplines, including supporting technologies, as well as contributions to other science and technology advances made possible by fusion research. Consideration should also be given to systematic inclusion of fusion in energy-related instructional materials used in schools across the nation.

SUMMARY

This chapter describes an expanded organizational structure for the U.S. DOE Office of Fusion Energy Sciences (OFES) that implements a research program evolving toward a long-term plan for fusion energy and strengthens community participation in the burning plasma science, materials science, fusion nuclear science and technology, and the engineering sciences needed to realize an economical pathway to fusion electricity for the nation. The committee arrived at several conclusions:

> **Finding:** The program management strategy for the coming decades would benefit from exploiting the benefits of U.S. ITER participation as a full partner, while advancing a coordinated domestic research program directed at elements of a fusion power system not addressed by ITER.
>
> **Finding:** The recommended expansion in scope and interconnected programs within OFES will necessitate reconsideration of management and planning to ensure coordination between programs and efficient progress.
>
> **Finding:** Success in fusion energy and global leadership will require opportunities for the U.S. to maintain and expand its institutional knowledge in the design, construction and successful operation of experimental facilities on a gradation of scales.
>
> **Finding:** Community input in setting technical priorities (including initiation of new projects and facilities and sunsetting those no longer needed) is essential for a healthy fusion energy program because of the interrelated nature of fusion energy technologies. Ongoing community engagement will further serve to promote community unity and foster morale and retention of a creative and productive workforce.
>
> **Finding:** Opportunities exist to encourage and support private investment in fusion energy development and the focused, goal-oriented approach from U.S. industry, which is beneficial to fusion energy development.
>
> **Finding:** Science and engineering resulting from U.S. investment in fusion energy research will have synergies and benefits to other disciplines. Specific examples include: exascale computing, high field magnets employing high temperature superconductors (HTS), robotics, high-performance materials, low temperature plasmas and astrophysical plasmas.

Based on these findings, the committee makes the following recommendations:

Recommendation: The committee recommends a new division within U.S. DOE/FES to manage and organize research developing technologies needed to improve and fully enable the fusion power system.

Recommendations: The U.S. DOE/FES should establish a formal strategic planning process by which, at regular intervals, respected scientific and technical leaders review progress on short- and long-term goals. This should include consideration of upgrades to and new U.S.-based research facilities needed to advance science and technology in support of fusion energy. Community input should be an essential element of this process.

Recommendation: The U.S. DOE/FES should establish formal structures for regular communication with and among leaders of the research communities across the OFES program.

Based on the committee's observations of other programmatic ways to strengthen fusion research, the committee makes these additional recommendations:

Recommendation: It is recommended that the DOE Fusion Safety Standards be reviewed for consistency with current regulations, and updated to incorporate the community's increased knowledge of the performance of fusion systems and current fusion program needs. In parallel with the fusion pilot plant design effort, a licensing strategy should be developed that includes transition from DOE to NRC regulatory authority to ultimately allow for commercialization of fusion power.

Recommendation: In addition to continued participation in ITER, the U.S. government should explore partnerships with other existing and future facilities in Europe, Asia and the U.S. as a means of pooling expertise and resources in advancing specific aspects of fusion science and technology, including aspects of the tritium fuel cycle and the accompanying areas of fusion nuclear materials, plasma facing materials, fusion nuclear science and enabling technologies.

Recommendation: The U.S. DOE OFES should define mechanisms to manage assignment of intellectual property as a means to encourage both private and publicly funded researchers to establish mutually beneficial partnerships.

Recommendation: The U.S. DOE OFES should conduct outreach initiatives that engage the fusion research community and inform the nation of the realization of fusion an energy source is a united effort involving many disciplines, including advanced technologies and contributes broadly to national science and technology goals. Public awareness is a critical element in maintaining support for the fusion effort and associated expenditures, and for inspiring young students to consider pursuing careers in fusion energy, the fusion research community.

NOTES

1. FESAC subcommittee on transformative enabling capabilities toward fusion energy, FESAC Report: *Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy*, Department of Energy Office of Fusion Energy Sciences, February 2018.
2. From p. 126 of National Research Council. 2004. *Burning Plasma: Bringing a Star to Earth.* Washington, DC: The National Academies Press. https://doi.org/10.17226/10816.
3. See https://sites.google.com/site/usmfrstrategicdirections/home
4. Bader et al. , "Perspective on Magnetic Fusion Energy Directions from Early Career Fusion Scientists," White paper submitted to Committee on a Strategic Plan for U.S. Burning Plasma Research (2018)
5. Safety of Magnetic Fusion Facilities: Requirements, DOE-STD-6002 (1996)
6. Safety of Magnetic Fusion Facilities: Guidance, DOE-STD-6003 (1996)
7. Supplementary Guidance and Design Experience for this Fusion Safety Standards DOE-STD-6002-96 and DOE-STD-6003-96, DOE-STD-6004 (1999)
8. Final Report of the ITER Engineering Design Activities (EDA) (2001)
9. Burning Plasma Assessment Committee, "Burning Plasma: Bringing a Star to Earth," National Academies Press (Washington D.C., 2004).
10. "Status of University-based magnetic confinement research", White Paper submitted to NAS (2017)
11. Burning Plasma Assessment Committee, "Burning Plasma: Bringing a Star to Earth," National Academies Press (2004).
12. Greenwald et al., "Recommendations for ITER Experimental Operation, U.S. Team Formation and Participation," Burning Plasma Organization, 2015.
13. Fig. 2-2 from the "Annual Report on the State of DOE National Laboratories, DOE Report, January 2017.
14. Information about the Fusion Industry Association is available online https://www.fusionindustryassociation.org.
15. Binderbauer, M., et al., Phys. Rev. Lett. 105 045003 (2010)
16. Tuszewski, M., et al., Phys. Rev. Lett. 108 255008 (2012)
17. See https://www.cfs.energy
18. Wendt et al., "Applications of Fusion Energy Sciences Research," Fusion Energy Sciences Advisory Committee, U.S. DoE Office of Science (2015).

Appendixes

A

Statement of Task

A committee of the National Academies of Sciences, Engineering, and Medicine will be formed to study the state and potential of magnetic confinement-based fusion research in the United States and provide guidance on a long-term strategy for the field. The study will focus on research that supports understanding the magnetically confined burning plasma state but will take a broad view beyond plasma confinement science, and as such consider capabilities such as simulation and materials. Specifically, the committee will prepare an interim report that will:

1. Describe and assess the current status of U.S. research that supports burning plasma science, including current and planned participation in international activities, and describe international research activities broadly.
2. Assess the importance of U.S. burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

The committee will also prepare a final report, building on the interim report, which will:

1. Consider the scientific and engineering challenges and opportunities associated with advancing magnetic confinement fusion as an energy source, including the scientific and technical developments since the 2004 NAS[1] study on burning plasma research.
2. In two separate scenarios in which, after 2018, (1) the United States is a partner in ITER, and (2) the United States is not a partner in ITER: provide guidance on a long-term strategic plan (covering the next several decades) for a national program of burning plasma science and technology research which includes supporting capabilities and which may include participation in international activities, given the U.S. strategic interest in realizing economical fusion energy in the long term.

In doing the above, the committee will consider the priorities for the next ten years developed by the community and FES that were recently reported to Congress. The committee will also consider the current level of participation by U.S. scientists in international activities as well as what role international collaboration should play over the next 20 years. The committee will also consider the health of the domestic fusion research sectors (universities, national laboratories, and industry). Elements of any strategic plan for U.S. burning plasma research should ensure that the United States maintains a leadership role in this field. The committee may assume that economical fusion energy within the next several decades is a U.S. strategic interest. The committee may take into account how unanticipated events or innovations may necessitate mid-course re-directions. The committee will use the prior work of the Academies as well as that of FESAC and the domestic and foreign communities in its deliberations. The committee is not to compare fusion as an energy source against other current or potential energy sources. The committee will consider the budget implications of its guidance but will not make recommendations about the budget for burning plasma research itself. The committee will only consider magnetically confined burning plasma research as within its purview. The committee may make recommendations or offer comments on organizational structure and program balance, with accompanying supporting discussion of the evidentiary bases, as appropriate.

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before July 1.

B

Agendas from Committee Meetings and Site Visits

Meeting #1
June 5-6, 2017

Keck Center of the National Academies
500 5th Street NW
Washington, D.C

June 5, 2017

CLOSED SESSION

8:00 A.M.	Breakfast
9:00 A.M.	Discussion
12:00 P.M.	Lunch
1:00 P.M.	Discussion

OPEN SESSION

1:45 P.M.	Reconvene
2:00 P.M.	Perspective from DOE Fusion Energy Sciences, Ed Synakowski, DOE FES
3:00 P.M.	Break
3:15 P.M.	Perspectives from Capitol Hill, Adam Rosenberg and Emily Domenech, House Science, Space, and Technology
4:00 P.M.	Perspectives from the U.S. Burning Plasma Organization, Chuck Greenfield, General Atomics, and Amanda Hubbard, MIT
5:00 P.M.	Open public comments
5:30 P.M.	Break

CLOSED SESSION

6:30 P.M.	Committee dinner
8:30 P.M.	Adjourn for the day

June 6, 2017

CLOSED SESSION
This day is held entirely in closed session.

Meeting #2

August 29-31, 2017

Beckman Center of the National Academies
Irvine, California

August 29, 2017

CLOSED SESSION
8:00 A.M. Breakfast
9:00 A.M. Committee discussion

OPEN SESSION
9:30 A.M. Perspectives from the U.S. ITER Project, Ned Sauthoff, Oak Ridge National Lab
Perspectives from the ITER Organization, Bernard Bigot, Director General
10:30 A.M. Break
11:00 A.M. Perspective on Fusion Energy Strategy, Stewart Prager, Princeton University
12:00 P.M. Lunch
1:00 P.M. Perspective on Fusion Energy Strategy, Tony Taylor, General Atomics
2:00 P.M. Perspectives from University Fusion Associates, David Maurer, Auburn University
3:00 P.M. Break
3:30 P.M. Perspectives from the Virtual Laboratory for Technology, Phil Ferguson, Oak Ridge National Lab
4:30 P.M. Public comments

CLOSED SESSION
5:00 P.M. Discussion

OPEN SESSION
6:30 P.M. Dinner
8:30 P.M. Adjourn for the day

August 30, 2017

CLOSED SESSION
8:30 A.M. Committee discussion
6:00 P.M. Adjourn for the day

August 31, 2017

CLOSED SESSION
8:30 A.M. Committee discussion
2:00 P.M. Adjourn

Meeting #3

December 15-16, 2017

Omni Austin Downtown
Austin, TX

December 15, 2017

OPEN SESSION – Capital Ballroom
8:00 A.M. US Magnetic Fusion Research Strategic Directions Workshop

10:30 A.M. Break
12:30 P.M. Workshop Concludes

December 16, 2017

CLOSED SESSION – Austin Conference Room
8:00 A.M. Committee Discussion
12:30 P.M. Working Lunch

OPEN SESSION
1:30 P.M. Reception of the interim report, Jim Van Dam, DOE-Fusion Energy Sciences
2:15 P.M. Path forward for fusion Dennis Whyte, MIT's Plasma Science and Fusion Center
3:00 P.M. Princeton lab update, Richard Hawryluk, Princeton Plasma Physics Laboratory
3:45 P.M. Public Discussion
4:30 P.M. Break

CLOSED SESSION
5:00 P.M. Discussion

OPEN SESSION - Perry's Steakhouse
7:00 P.M. Dinner
9:00 P.M. Adjourn for the day

Meeting #4

February 1-2, 2018

ITER
St. Paul Lez Durance France

February 1, 2018

OPEN SESSION – ITER Council Room
9:00 A.M. Welcome from ITER Organization, Bernard Bigot, Director-General
9:15 A.M. Opening Remarks, Introductions, and Discussion of Agenda,
Michael Mauel and Melvyn Shochet, Study Committee Co-Chairs
9:30 A.M. Foundation of the EUROfusion Consortium, Sibylle Guenter, Max Planck Institut für Plasmaphysik
10:30 A.M. Break
11:00 A.M. Strategic Plan of the European Fusion Consortium, Tony Donné, EUROfusion
12:00 A.M. Lunch and General Discussion
1:30 P.M. European DEMO design activities, Gianfranco Federici, EUROfusion
2:30 P.M. Break
3:00 P.M. Overview of ITER Project and International Organization,
Bernard Bigot, Director-General, ITER
4:00 P.M. The Science of ITER, Tim Luce, Head of Science and Operations, ITER
5:00 P.M. General Discussion
6:00 P.M Break and Depart for Dinner
7:00 P.M. Committee Dinner - Le Jardin Mazarin
9:00 P.M. Adjourn for the day

February 2, 2018

OPEN SESSION – ITER Council Room
9:00 A.M. Tour of ITER Worksite Bernard Bigot, Director-General, ITER
10:30 A.M. Break
10:45 A.M. ITER Engineering Science and Breakthroughs
Gyung-Su Lee, Deputy Director-General, ITER
11:45 A.M. Lunch
1:15 P.M. Project Management, Hans-Henrich Altfeld, Head of Project Control Office, ITER
2:15 P.M. Summary and Conclusion, Bernard Bigot, Director-General, ITER
2:30 P.M. Break

CLOSED SESSION – ITER Council Room
3:00 P.M. Committee discussion
4:00 P.M. Adjourn and depart for hotel/airport;

Meeting #5

February 26-28, 2018

General Atomics (GA)
San Diego, CA

February 26, 2018

OPEN SESSION – GA Conference Room
8:00 A.M. Breakfast
9:00 A.M. Welcome from General Atomics and Discussion of Agenda
9:15 A.M. Research Plans of the DIII-D National Team, Richard Buttery, GA
10:15 A.M. Vision for Fusion Research at General Atomics, Dave Hill, GA
11:15 A.M. Break
11:30 A.M. Strategic elements/Approaches of the U.S. Fusion Program, Mickey Wade, GA
12:15 P.M. Lunch and General Discussion
1:30 P.M. Japanese Fusion Energy Strategy, Yuichi Ogawa, Univ. Tokyo
2:30 P.M. Republic of Korea Fusion Energy Strategy, Yong-Seok Hwang, Seoul National University.
3:30 P.M. Break
4:00 P.M. Break and depart for tour of DIII-D facility
6:30 P.M. Working dinner - Eddie V's Prime Seafood
8:00 P.M. Adjourn for the day

February 27, 2018

CLOSED SESSION– GA Conference Room
8:30 A.M. Committee discussion
10:00 A.M. Break
10:15 P.M. Committee discussion
12:00 PM Lunch

February 28, 2018

CLOSED SESSION– GA Conference Room

8:00 A.M.	Committee discussion

OPEN SESSION

9:00 A.M.	Tour of Magnet Technology Center

CLOSED SESSION– GA Conference Room

11:00 A.M.	Committee Discussion
12:00 P.M.	Working Committee Lunch
1:00 P.M.	Committee Discussion
3:00 P.M.	Adjourn

Meeting #6

April 11-13, 2018

Princeton Plasma Physics Laboratory
Princeton, NJ

April 11, 2018

OPEN SESSION – Lyman Spitzer Building, Conference Room B318

9:00 A.M.	Welcome from PPPL and Discussion of Agenda
9:15 A.M.	Overview Vision of PPPL in Long-Term Fusion Strategy, Mike Zarnstorff, PPPL
9:45 A.M.	Options and Strategies towards Fusion Net-Electricity , Jon Menard, PPPL
10:30 A.M.	NSTX-U Research and Operation Plan, Stefan Gerhardt, PPPL
11:15 A.M.	Break
11:30 A.M.	Advanced Scientific Computing Strategy for Fusion, Amitava Bhattacharjee, PPPL
12:15 P.M.	Lunch
12:15 P.M.	Trying for Upside Potential in Controlling Fusion, Nat Fisch, PPPL

CLOSED SESSION

1:30 P.M.	Committee Discussion Committee and Staff

OPEN SESSION - Witherspoon Grill

6:30P.M.	Committee working dinner
8:00 P.M.	Adjourn for the day

August 12, 2018

CLOSED SESSION

8:30 A.M.	Committee discussion

OPEN SESSION

1:00 P.M.	High-Field Development Strategy for Fusion, Martin Greenwald, MIT
1:45 P.M.	Investor-MIT Partnership for Fusion Development, Bob Mumgaard, CFS
2:15 P.M.	Strategic Prospects for HTS Magnets for Fusion, Soren Prestemon, LBNL
3:00 P.M.	Break

3:15 P.M.	Plasma-Materials and Divertor Options for Fusion, Juergen Rapp ORNL
4:00 P.M.	Liquid Metal Technology Strategy for Fusion, Mike Jaworski, PPPL
4:45 P.M.	Public comment

CLOSED SESSION

5:00 P.M.	Committee Discussion Committee and Staff

OPEN SESSION

6:00	Tour of NSTX-U and PPPL Laboratory
7:30	Adjourn for the day

Meeting #7

June 12-14, 2018

Keck Center of the National Academies
Washington D.C

June 12, 2018

CLOSED SESSION – Keck 201

9:00 A.M.	Welcome and Discussion of Agenda, Co-chairs, Mike Mauel and Mel Shocket
9:15 A.M.	Current summary of findings and recommendations
10:15 A.M.	Break
10:30 A.M.	High-level discussion: Does the draft reflect our findings and recommendations?
12:00 P.M.	Lunch
1:00 P.M.	Review of Chapter 2
2:30 P.M.	Break
2:45 P.M.	Review of Chapter 3
4:15 P.M.	Review of Chapter 4
5:45 P.M.	Break for dinner
6:30 P.M.	Committee working dinner - Ruth's Chris Steak House
8:00 P.M.	Adjourn for the day

June 13, 2018

CLOSED SESSION – Keck Room 201

8:30 A.M.	Review of Chapter 6
10:15 A.M.	Break
10:30 A.M.	Review of Summary
12:00 P.M.	Lunch
1:00 P.M.	2nd Review of findings and recommendations
2:30 P.M.	Break
2:45 P.M.	2nd Discussion: Does the draft reflect our findings and recommendations?
4:15 P.M.	Further Discussion: what needs to be drafted?
5:45 P.M.	Adjourn for the day

June 14, 2018

CLOSED SESSION – Keck Room 101

8:00 A.M.	Breakfast available in meeting room
9:00 A.M.	High-level discussion: summary and thoughts
10:30 A.M.	Break
11:00 A.M.	Discussion: further assignments and schedule
12:00 P.M.	Lunch
1:00 P.M.	Wrap up/continued discussion of next steps
2:00 P.M.	Adjourn

C

Strategic Planning for U.S. Burning Plasma Research from 2000 to 2018

This appendix provides background to various strategic planning activities for the U.S. burning plasma research effort beginning with the 2001 FESAC Report on *Burning Plasma Physics*[1] to the 2015 strategic planning perspective provided to Congress by the U.S. DOE Office of Science in response to the Consolidated Appropriations Act, 2014.[2] Background to U.S. fusion strategic planning is also available in Appendix D: "Fusion Community Recommendations" of the 2004 NAS Report of the *Burning Plasma Assessment Committee*[3] and in Chapter 1 of the committee's Interim Report.

The following background to U.S. strategic planning activities is organized into three parts: (*i*) Achievement of Government Consensus to Join ITER, (*ii*) U.S. Planning during the ITER Design Review and Start of Construction, and (*iii*) Management Reforms and the Updated ITER Cost and Schedule.

Achievement of Government Consensus to Join ITER

In October 2000, Mildred Dresselhaus, Director of the Office of Science requested FESAC address the scientific issues of burning plasma physics. In her letter, Dresselhaus noted the U.S. magnetic fusion community has recognized burning plasma physics as the next frontier of fusion research and quoted the recommendation of the 1990 Fusion Policy Advisory Committee for "construction as soon as possible of the U.S. Burning Plasma Facility." In addition to reporting the scientific issues to be addressed by a burning plasma physics experiment, FESAC was charged to address how the U.S. program should be used to assist the community in preparations for an assessment in 2004, as recommended in the 1999 FESAC Subcommittee on Priorities and Balance.[4]

The main conclusion of the 2001 FESAC Report on *Burning Plasma Physics* (p. 7) was:

> *The U.S. fusion program, and indeed the world fusion program, is technically and scientifically ready to proceed NOW with a burning plasma experiment.* This is the logical next step on the path to fusion energy. The key physics and engineering questions have been known since the mid 1980's. They have been investigated theoretically during the interim period. They have been investigated on existing experiments, although often one at a time or in reduced performance regimes because of experimental limitations. Further progress requires a new, large scale burning plasma experiment. Thus, the key question is not "Are we ready?" but instead "How should we proceed?"

The 2001 FESAC Burning Plasma Physics Report further said (*i*) a workshop should be held for the scientific and technological examination of proposed burning plasma experimental designs and to provide community input and endorsement to FESAC planning activities, and (*ii*) that the DOE initiate a

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[1] Report of FESAC Subcommittee, *Review of the Burning Plasma Physics*, DOE/SC-0041. Washington, D.C.: U.S. Department of Energy, 2001; available online at https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/134/46134990.pdf

[2] U.S. DOE Report to Congress, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, (December 2015); available online at https://fire.pppl.gov/FES_10Year_Perspective_2015.pdf

[3] National Research Council. 2004. *Burning Plasma: Bringing a Star to Earth*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10816.

[4] Report of the FESAC *Panel on Priorities and Balance*, (1999); available as Baker, C., Davidson, R., Dean, S. et al. *Journal of Fusion Energy* (1999) 18: 65. https://doi.org/10.1023/A:1018831113757

review by a National Research Council committee with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design. The 2001 FESAC Report was highly influential, and the U.S. DOE adopted both follow-on planning activities.

In 2002, the U.S. fusion community organized a fusion summer study, co-sponsored by the APS Division of Plasma Physics, the ANS Fusion Energy Division, and the U.S. DOE/FES. At the same time, DOE Office of Science's Acting Director, James Decker, charged FESAC to establish a high-level panel to recommend a strategy for burning plasma experiments. The FESAC Panel on a *Burning Plasma Program Strategy to Advance Fusion Energy*[5] considered three options for a burning plasma experiment at different sizes and levels of readiness and concluded (p. 3), "Since ITER is at an advanced stage, has the most comprehensive science and technology program, and is supported internationally, we should now seek to join the ITER negotiations with the aim of becoming a partner in the undertaking, with technical, programmatic and timing considerations" that included U.S. participation in the full range of activities, proposing and implementing science experiments, reviewing the overall cost of the ITER project, and concluding that ITER is highly likely to proceed to construction.

On September 2002 and upon release of the FESAC Report on a *Burning Plasma Program Strategy to Advance Fusion Energy*, Raymond Orbach, Director of the Office of Science, tasked a committee of National Academies to "carry out an assessment of a program of burning plasma experiments and its role in magnetic fusion research." The NAS Burning Plasma Assessment Committee was instructed to complete an Interim Report (see Appendix E of Ref. 3) containing "advice to the Department of Energy regarding reentering negotiations to be a participant in the multinational burning plasma experiment (ITER)." The NAS Burning Plasma Assessment Committee 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." But the NAS committee was not asked to evaluate fusion as an energy option. This task was given to a FESAC subcommittee, also in September 2002, resulting in the 2003 Report of the FESAC Subcommittee for a *Plan for the Development of Fusion Energy*.[6] While the NAS Burning Plasma Assessment Committee was asked to consider the importance and readiness to undertake a burning plasma experimental program, the FESAC subcommittee was asked "to comment, from our present state of understanding of fusion, on the prospects and practicality of electricity into the U.S. grid from fusion in 35 years."

The Interim Report of the NAS Burning Plasma Assessment Committee was released on December 20, 2002 and recommended "the United States enter into ITER negotiations while the strategy for an expanded U.S. fusion program is further defined and evaluated." This recommendation was subject to three conditions: (*i*) "a strategically balanced 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", (*ii*) "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", and (*iii*) "the United States should pursue an appropriate level of involvement in ITER, which at a minimum would guarantee access to all data from ITER, the right to propose and carry out experiments, and a role in producing the high-technology components of the facility, consistent with the size of the U.S. contribution to the program."

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[5] FESAC Panel Report on a *Burning Plasma Program Strategy to Advance Fusion Energy* (DOE/SC-0060, September 2002); also available at Prager, S., Baker, C., Baldwin, D. et al., *J Fusion Energy* (2001) 20: 85. https://doi.org/10.1023/A:1021398608479

[6] Report of the FESAC Fusion Development Panel (March 2003), A Plan for the Development of Fusion Energy, DOE/SC-0074; also available as Goldston, R., Abdou, M., Baker, C. et al. *Journal of Fusion Energy* (2002) 21: 61. https://doi.org/10.1023/A:1025038002187 .

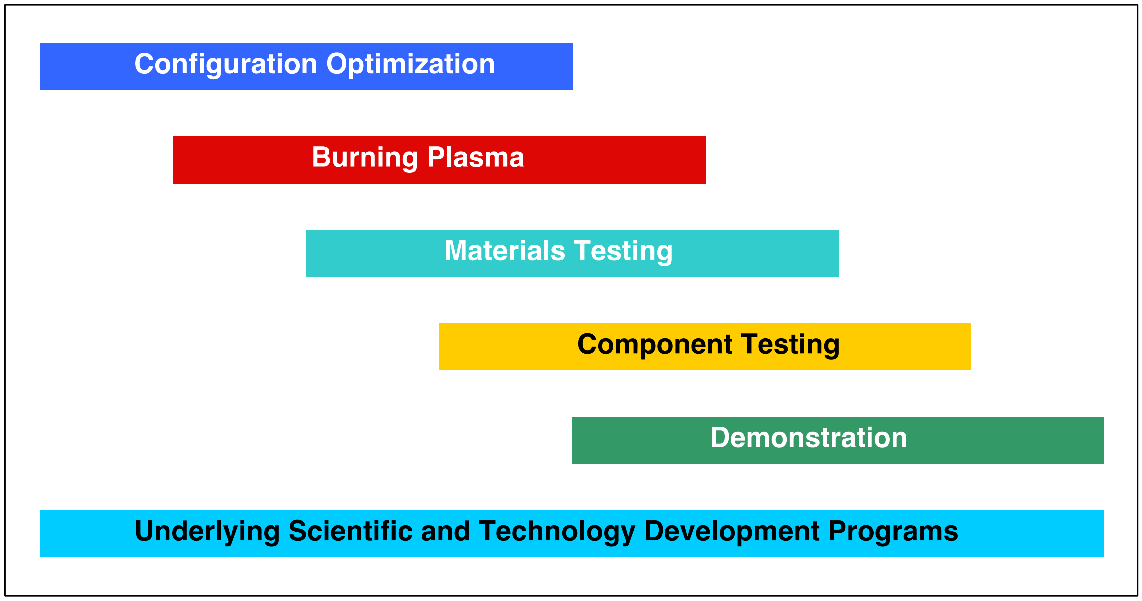

FIGURE C.1 The overlapping scientific and technological challenges needed in the fusion development path described in the 2003 FESAC Report (p. 7 of Ref. 6). In order to demonstrate fusion electricity, materials testing research and fusion component testing should accompany burning plasma research.

The 2003 FESAC Report for *A Plan for the Development of Fusion Energy* presented a comprehensive fusion development strategy that included both inertial fusion energy (IFE) and magnetic fusion energy (MFE). The key conclusion of the plan was (p. 6 of Ref. 6) was "to develop fusion energy on this timescale [35 years], it is imperative to have a strong balanced program that develops fusion science and technology in parallel". The committee found a set of overlapping scientific and technological challenges that determined the development path for fusion energy. These challenges were presented in Fig. A.1 and comprised research in configuration optimization, burning plasma science, materials testing, fusion component testing, demonstration of environmentally and economically attractive fusion energy, and the underlying science and technology programs in basic plasma science, theory and simulation, materials science, and engineering science.

Six weeks after the release of the NAS Burning Plasma Interim Report, on January 30, 2003, President George W. Bush announced "that the United States will join an ambitious international research project to harness the promise of fusion energy, the same form of energy that powers the sun." The President's announcement described ITER as "the largest and most technologically sophisticated fusion experiment in the world." The President also acknowledged the National Academies recommendation for U.S. participation in ITER and further explained, "This step is critical to the development of fusion as a viable energy source. Recent scientific developments have advanced knowledge of this field to the point that scientists now believe ITER can demonstrate the feasibility of this technology as part of an ongoing effort to develop a practical energy-generating device."

Later that year, Raymond Orbach requested FESAC to assist in establishing priorities for the fusion program in light of the recommendation of the 2004 NAS Burning Plasma Committee for a new effort to integrate ITER into the U.S. domestic program. The 2005 FESAC Report on *Scientific*

Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program[7] described overarching themes, asked topical scientific questions, and defined six campaigns to plan, organize, and coordinate research activities. The committee's recommendations called for "a research program that encompasses a broad range of key scientific questions," identified high-priority activities for the domestic research program that would be enhanced with additional funding, and stated "the need for additional major domestic experimental facilities."

Achievement of government consensus on rejoining ITER, along with broad support within the U.S. scientific community, was a major accomplishment over the past decade. The committee's key recommendation was: "The United States should participate in the International Thermonuclear Experimental Reactor (ITER) project. If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced U.S. fusion science program." Following this recommendation, the U.S. Department of Energy *Twenty-Year Outlook*[8] listed ITER as the highest priority within the Office of Science in 2003 and, again, in 2007.[9]

The international agreement to build and operate a burning plasma experiment was finally formalized in Paris with the signing of the *Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project* on November 2006.[10] The ITER International Fusion Energy Organization (IO) is a public international organization, with limited privileges and legal immunities, involving the U.S. with China, the European Union, India, Japan, the Republic of Korea and the Russian Federation. At the signing ceremony, DOE Undersecretary for Science Raymond Orbach explained, "ITER is the first stand-alone, truly international, large-scale scientific research effort in the history of the world."

U.S. Planning During the ITER Design Review and Start of Construction

As predicted by the 2004 NRC Burning Plasma Assessment Committee (p. 12 of Ref. 3), "once the [ITER] decision is made, fulfilling the international commitment to help construct the ITER facility and participate in the ITER program will necessarily become the highest priority in the program." This new priority within the United States fusion energy sciences program following the ITER agreement resulted in several planning activities, both (*i*) to guide U.S. participation in the ITER project and (*ii*) to develop and define U.S. fusion research that would accompany ITER.

In response to the Energy Policy Act of 2005, DOE Undersecretary for Science Raymond Orbach tasked the National Academies to review the plan for U.S. Community Participation in the ITER Program[11] that was developed by the U.S. Burning Plasma Organization (USBPO). The NAS committee made several recommendations (pp. 2-4) including that steps should be taken to "seek greater funding stability for the international ITER project to ensure that the United States remains able to influence the developing ITER research program, to capitalize on research at ITER to help achieve U.S. fusion energy goals, to participate in obtaining important scientific results on burning plasmas from ITER, and to be an effective participant in and beneficiary of future international scientific collaborations." The committee also noted important considerations not reflected in the DOE plan for U.S. participation in ITER should

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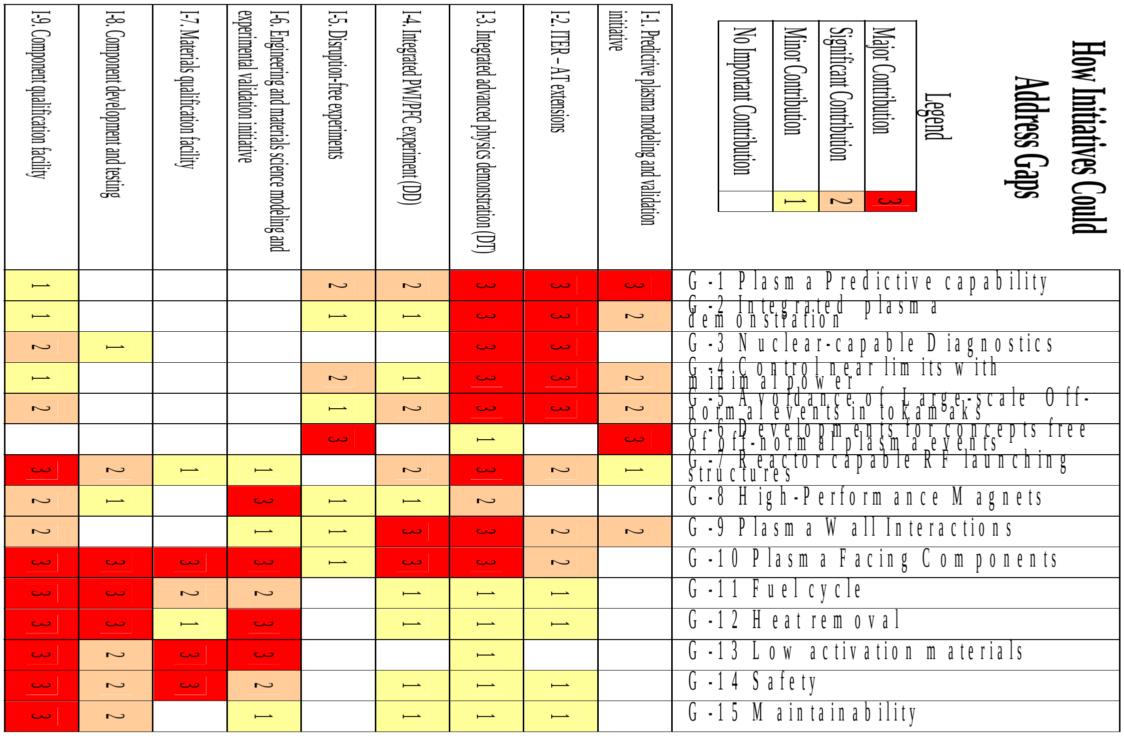
[7] FESAC (2005), Report on *Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program*; available as Baker, C., Prager, S., Abdou, M. et al. *J Fusion Energ* (2005) 24: 13. https://doi.org/10.1007/s10894-005-6922-z

[8] DOE, *Facilities for the Future—A Twenty Year Outlook,* Office of Science, Washington, D.C., November 2003.

[9] *Facilities for the Future - A Twenty Year Outlook*, U.S. DOE Office of Science (November, 2003).

[10] https://www.iaea.org/sites/default/files/publications/documents/infcircs/2007/infcirc702.pdf

[11] National Research Council. 2009. *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12449.



How Initiatives Could Address Gaps

Legend

3	Major Contribution
2	Significant Contribution
1	Minor Contribution
	No Important Contribution

	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

FIGURE C.2 Figure 1 (p. 20) from the 2007 FESAC Report on *Priorities, Gaps and Opportunities Towards A Long-Range Strategic Plans for Magnetic Fusion Energy*.[12] The effectiveness of nine potential initiatives to address all of the scientific and technical gaps to fusion energy development illustrates that accompany research in addition to ITER is needed.

be addressed and include "existing gaps in planning for a Demonstration Power Plant, dissemination of information on and the results of ITER research activities to the broader scientific community, and planning for the recruitment and training of young scientists and engineers."

Five subcommittees of FESAC provided important strategic guidance for the research needed to advance fusion energy science alongside ITER. These six subcommittees completed their reports in the five years following the signing of the ITER agreement:

- Report of the 2007 FESAC Subcommittee on *Priorities, Gaps and Opportunities Towards A Long-Range Strategic Plans for Magnetic Fusion Energy,*[12]which submitted four recommendations (pp. 6-7): (*i*) "a long-term and detailed strategic plan should be developed and implemented as soon as possible," (ii) the "plan should recognize and address all scientific challenges of fusion energy including fusion engineering, materials sciences and plasma physics," (iii) the "plan should include bold steps and encourage adoption of major new initiatives or construction of new facilities in order to resolve scientific challenges," and (iv) "nine potential initiatives, ranging from key topics in fusion science and engineering to large, integrated plasma experiments exploring aspects of the fusion reactor environment."

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[12] Report of the 2007 FESAC Subcommittee on *Priorities, Gaps and Opportunities Towards A Long-Range Strategic Plans for Magnetic Fusion Energy*; available online at https://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf

- Report of the 2007 FESAC Subcommittee on *Fusion Simulation Project (FSP),*[13] which recommended joint U.S. DOE/FES-ASCR program activities (p. 1) "to develop advanced software designed to use leadership class computers for carrying out multi-scale physics simulations to provide information vital to delivering a realistic integrated fusion simulation model with unprecedented physics fidelity."
- Report of the 2008 FESAC *Toroidal Alternatives Panel*,[14] which made several general findings of the quality, benefit, and status of various configurations for magnetic confinement fusion.
- DOE Office of Science, 2009 Report of the *Research Needs Workshop for Magnetic Fusion Energy (ReNeW),*[15] which involving some 200 scientists from universities, national laboratories and private industry to develop a portfolio of research activities for U.S. research in magnetic fusion for two decades. The report characterized three "ReNeW thrusts" (p. 9): (*i*) "advancement in fundamental science and technology", (*ii*) "confrontation with critical fusion challenges", and (*iii*) "the potential for major transformation of the program – such as altering the vision of a fusion reactor, or shortening the time scale for fusion's realization."
- Report of the 2012 FESAC subcommittee on *Materials Science and Technology Research Opportunities Now and in the ITER Era: A Focused Vision on Compelling Fusion Nuclear Science Challenges*,[16] which made three overarching recommendations (pp. vi-vii): (*i*) as fusion nuclear science matures from concept exploration studies to more complex proof of principle studies, it is appropriate to focus R&D on front-runner concepts; (*ii*) numerous fusion nuclear science feasibility issues can be effectively investigated during the next 5 to 10 years by efficient use of medium-scale facilities; and (*iii*) the key mission of the next step U.S. device should be to explore the integrated response of tritium fuel, materials and components in the extreme fusion environment in order to provide the knowledge bases to contain, conquer, harness and sustain a thermonuclear burning DT plasma at high temperatures.
- Report of the 2012 FESAC subcommittee on *Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era*,[17] which considered the question "what additional international collaborations should be pursued by a US FES program that is already expecting to be dominated by the large international ITER collaboration?" and identified three compelling opportunities for international collaboration (pp. 7-9): (*i*) extending high performance regimes to long pulse, (*ii*) development and integration of plasma wall solutions for fusion, and (*iii*) burning plasma research in advance of ITER.

The 2007 FESAC Report on *Priorities, Gaps and Opportunities* "found remarkable progress has been made by the [fusion research] program but recognized that formidable challenges remain." The report organized the key scientific and technical questions that need to be answered into three themes: creating predictable high-performance steady-state plasmas, taming the plasma material interface, and harnessing fusion power. An important conclusion of the FESAC subcommittee was multiple initiatives

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[13] ESAC (2007) *Report on Fusion Simulation Project (FSP)*; https://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_fsp_report.pdf.

[14] FESAC *Toroidal Alternatives Panel* (2008); https://science.energy.gov/~/media/fes/fesac/pdf/2008/Toroidal_alternates_panel_report.pdf

[15] DOE Office of Science, Report of the *Research Needs Workshop for Magnetic Fusion Energy (ReNeW),* (Bethesda, Maryland – June 8-12, 2009); https://science.energy.gov/~/media/fes/pdf/workshop-reports/Res_needs_mag_fusion_report_june_2009.pdf

[16] FESAC Report (2012) on *Materials Science and Technology Research Opportunities Now and in the ITER Era: A Focused Vision on Compelling Fusion Nuclear Science Challenges*; https://science.energy.gov/~/media/fes/pdf/workshop-reports/20120309/FESAC-Materials-Science-final-report.pdf.

[17] FESAC Report (2012) on *Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era*; https://science.energy.gov/~/media/fes/pdf/workshop-reports/20120309/Intl_Collab_Final_SCSC-PRINT.pdf.

were needed to fully address the scientific and technical gaps in fusion development. Fig. A.2 shows the effectiveness of the nine potential initiatives in addressing the key scientific and technical questions. While the ITER burning plasma research program addresses many questions, additional research should accompany ITER to answer questions related to the plasma material interface and the technologies to harnessing fusion power.

Simultaneous with the above-mentioned U.S. research planning activities, the United States contributed to the international review and update of the ITER physics basis and design. The initial ITER physics basis was published as nine chapters of *Nuclear Fusion* in 1999[18] and represented the combined expert knowledge of the international community for the ITER project. This physics basis was available to the 2004 NAS Burning Plasma Assessment Committee. With the signing of the ITER Joint Implementing Agreement, the International Tokamak Physics Activity (ITPA) Coordinating Committee updated the ITER physics basis, which appeared in 2007 as nine chapters (and 413 pages) in a special issue of *Nuclear Fusion*.[19] The ITER design review also resulted in topics affecting near-term procurement arrangements including poloidal field coil requirements, vertical stability, the effect of toroidal field ripple on thermal confinement, first wall material choice, disruptions, and disruption mitigation. [20]

Shortly after an international design review was completed in 2008, ITER construction began in 2010 in Cadarache, France.[21] In 2012, by French Order, ITER became the first of a kind licensed basic nuclear fusion facility.[22]

Management Reforms and the Updated ITER Cost and Schedule

Recent U.S. fusion energy strategic planning has been difficult because ITER construction costs have increased significantly and the construction schedule has significantly drawn-out. The increased construction cost for ITER has forced choices among program priorities and limited funding for new facilities.

In May 2013, a bipartisan group of leaders in the U.S. Senate requested the Government Accountability Office to investigate the cost and feasibility of ITER and its effect on U.S. fusion programs.[23] The senators wrote, "At a time when federal budgets for research are likely to be constrained for the foreseeable future, concerns have been raised that funding for other U.S. fusion energy science programs and user facilities have, and may continue to be, cut to pay for increasing ITER costs." The GAO recommended[24] that "DOE formally propose the actions needed to set a reliable international project schedule and set a date to complete the U.S. fusion program's strategic plan."

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[18] ITER Physics Basis Editors, ITER Physics Expert Group Chairs and Co-Chairs, ITER Joint Central Team, *Chapter 1: Overview and summary*, *Nuclear Fusion* 39, 2137 (1999); https://doi.org/10.1088/0029-5515/39/12/301.

[19] K. Ikeda, (2007), "Preface: Progress in the ITER Physics Basis," *Nuclear Fusion* 47, (2007); http://doi.org/10.1088/0029-5515/47/6/E01

[20] R. Hawryluk, et al., "Principal physics developments evaluated in the ITER design review," *Nuclear Fusion* 49, 065012 (2009); http://doi.org/10.1088/0029-5515/49/6/065012.

[21] M. Banks, "Construction begins, but ITER's costs spiral," *Phys. World*, 23(7), 10 (2010).

[22] P. Wouters *et al* (2017), "Implementation at ITER of the French Order of 7 February 2012, concerning basic nuclear installations within the European Domestic Agency," *Nucl. Fusion* 57, 100401; https://doi.org/10.1088/1741-4326/aa64fc

[23] See Newsroom Report from U.S. Senate Committee on Energy and Natural Resources, May 3, 2013, available online at https://www.energy.senate.gov/public/index.cfm/2013/5/senators-request-gao-investigation-of-costs-at-experimental-fusion-reactor

[24] U.S. Government Accountability Office, Fusion Energy: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor, Report to Congress, GAO-14-499, Washington, D.C., June 2014; available online https://www.gao.gov/products/GAO-14-499.

In response to cost and schedule concerns, the ITER Council charged an independent team, chaired by William Madia, former director of Oak Ridge National Laboratory and Stanford University vice president for the Stanford Linear Accelerator Center, to determine the causes for ITER's cost increases and schedule delays and to make management recommendations. These recommendations resulted in significant management improvements by the ITER Council and the appointment of Bernard Bigot as the new ITER director in March 2015. The ITER Council approved a new Updated Long-Term Schedule (ULTS) to first plasma in June 2016, and the U.S. DOE was able to approve the project execution plan for U.S. contributions to ITER in January 2017.[25] A measure of the success of ITER's management reforms is the fact that two years after the creation of the updated long-term schedule, the project remains on schedule for first plasma in 2025 and, since January 2016, has achieved all 33 scheduled project milestones.[26]

While ITER management reforms have been successful, recent strategic planning efforts in the United States have been less successful. As noted by the 2014 GAO report, "Without a strategic plan for the U.S. fusion program, DOE does not have information to create an understanding among stakeholders about its plans for balancing the competing demands the program faces with the limited available resources or to help improve Congress' ability to weigh the trade-offs of different funding decisions for the U.S. ITER Project and overall U.S. fusion program."

Responding to a request from the Office of Science, the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science[27] recommended three new U.S. facilities as "absolutely central" to world-leading fusion science: (*i*) a fusion materials irradiation facility, which would "transform nuclear material science and address critical gaps in irradiation capability needed to qualify materials for future science missions"; (*ii*) a fusion nuclear science facility (FNSF) , which would "provide the first-ever access to the integrated controlled thermonuclear fusion environment, which is characterized by strong couplings among high temperature plasma properties, plasma-material interactions, fusion neutron science and extreme material alterations and damage"; and (*iii*) a quasi-symmetric stellarator experiment, which would "evaluate a pathway toward producing steady, quiescent magnetically-confined fusion plasmas by scientific optimization of the underlying toroidal magnetic field geometry". Each of these recommended facilities would have created new opportunities to enhance or establish U.S. leadership in plasma and fusion science; however, none were adopted or pursued.

Then, responding to a Congressional request in the FY2014 Omnibus Appropriations Act, the U.S. DOE Office of Science asked FESAC to prioritize among research program elements defined by U.S. DOE FES assuming continued participation in ITER and include views on new facilities, initiatives, and facility closures. The resulting FESAC Strategic Panel Report[28] was controversial and recommended a strategy that would "transition the U.S. to a fusion energy program bounded by realistic budgets" and the start of a fusion nuclear science subprogram that would provide the scientific and technological basis for a Fusion Nuclear Science Facility (FNSF) as a critical step towards commercial power. In its transmittal letter, the Acting Chair of FESAC at the time wrote, "the lack of adequate consensus on top-level vision, strategy, and priorities makes it difficult for more technically oriented groups … to achieve widespread acceptance of recommended strategic initiatives and associated program-wide FES investments."

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[25] DOE, *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, Office of Science, Fusion Energy Sciences, Washington, D.C., January 2017.

[26] ITER Council Press Release (21 June 2018), available online: https://www.iter.org/doc/www/content/com/Lists/list_items/Attachments/777/2018_06_IC-22.pdf

[27] DOE, Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science, (March, 2013), available online: https://science.energy.gov/~/media/fes/fesac/pdf/2013/FESAC_Facilities_Report_Final.pdf

[28] DOE, Report on Strategic Pla*nning: Priorities Assessment and Budget Scenarios*, (October 2014), online: https://science.energy.gov/~/media/fes/fesac/pdf/2014/October/FESAC_strategic_planning_rept_dec14.pdf

The U.S. DOE/FES presented its current vision for fusion research to Congress in 2015.[29] The overall mission is to "expand the fundamental understanding of matter at very high temperatures and densities and build the scientific foundation needed to develop a fusion energy source." United States fusion research emphasizes two frontiers in burning plasma science: "the physics of self-heated burning plasma state" using ITER as the vehicle for gaining access to this state, and the "great scientific challenge for fusion is to develop materials that can tolerate the extreme conditions created by burning plasma in a fusion reactor." The majority of the U.S. DOE/FES program budget contributes to developing the predictive understanding needed for ITER operations and providing solutions to high-priority ITER research needs. A smaller element, called "Discovery Plasma Science," represents about 15% of the annual fusion budget and supports research that advances fundamental understanding of ionized matter, or plasma, in support of non-fusion applications. The U.S. DOE Office of Science *Ten-Year Strategic Vision* to Congress in 2015 emphasizes three continuing research thrusts: controlling transient events, the interface between fusion plasma and the surrounding material structures, and experimentally validated predictive simulations using massively parallel computers. This *Ten-Year Strategic Vision* benefited from three community workshop reports on: (*i*) *Science Challenges and Research Opportunities in Plasma Materials Interactions,*[30] (*ii*) *Integrated Simulations for Magnetic Fusion Energy Sciences*,[31] and (*iii*) *Transients in Tokamak Plasmas.*[32] In addition, FESAC completed a report titled *Applications of Fusin Energy Sciences Research: Scientific Discoveries and New Technologies Beyond Fusion*,[33] which identified areas of fusion energy sciences with broad impact on fields of science, technology and engineering not directly associated with fusion energy. While the U.S. DOE Office of Science *Ten-Year Strategic Vision* highlights important areas of research for the next decade, the U.S. DOE has not presented a plan for research and technology programs needed to progress beyond ITER to a source of fusion power nor started a fusion nuclear science subprogram leading to a new facility and to progress towards commercial power that was recommended by FESAC.[34]

At the end of 2015, the question of U.S. partnership in the ITER project was still unresolved, and Congress requested "the Secretary of Energy to submit to the Committees on Appropriations of both Houses of Congress a report recommending either that the Unites States remain a partner in the ITER project after October 2017 or terminate participation."[35] The Secretary's report was delivered to Congress in May 2016[36] and opened with the statement, "ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power." The Secretary of Energy recommended that the U.S. remain a partner in the ITER project through FY 2018 and acknowledged the significant construction progress made at ITER and the substantial improvements

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[29] DOE, The Office of Science's Fusion Energy Sciences Program: *A Ten-*Year Perspective, Report to Congress, Washington, D.C., December 2015.

[30] U.S. DOE/FES Report on *Science Challenges and Research Opportunities in Plasma Materials Interactions* (May, 2015); available online at https://science.energy.gov/~/media/fes/pdf/workshop-reports/2016/PMI_fullreport_21Aug2015.pdf.

[31] U.S. DOE/FES Report on *Integrated Simulations for Magnetic Fusion Energy Sciences* (June, 2015); available online at https://science.energy.gov/~/media/fes/pdf/workshop-reports/2016/ISFusionWorkshopReport_11-12-2015.pdf.

[32] U.S. DOE/FES Report on *Transients in Tokamak Plasmas* (June 2015); available online at https://science.energy.gov/~/media/fes/pdf/program-news/Transients_Report.pdf.

[33] FESAC Report (2015) on *Applications of Fusion Energy Sciences Research Scientific Discoveries and New Technologies Beyond Fusion*; available online at https://science.energy.gov/~/media/fes/fesac/pdf/2015/2101507/FINAL_FES_NonFusionAppReport_090215.pdf.

[34] (*p.* 18) DOE, The Office of Science's Fusion Energy Sciences Program: *A Ten-Year Perspective,* Report to Congress, Washington, D.C., December 2015.

[35] *Consolidated Appropriations Act, 2016,* (129 STAT. 2410), Public Law 114-113, December 19, 2015.

[36] U.S. Department of Energy, *U.S. Participation in the ITER Project*, Report to Congress, Washington, D.C., May 2016.

of ITER project management, but also noted significant technical and management risks remain. Continued ITER membership of the Unites States past FY 2018 awaits determination if project performance will be sustained and whether the larger costs needed for U.S. obligations for ITER construction can be accommodated in future budgets for the DOE Office of Science. Additionally, the Secretary's report requested advice from the National Academies and the establishment of the Committee on a Strategic Plan for U.S. Burning Plasma Research, and the J. Stephen Binkley, acting director of the U.S. DOE Office of Science, requested a report from FESAC "identifying the most promising transformative enabling capabilities for the U.S. to pursue that could promote efficient advance towards attractive fusion energy."[37]

The project cost and schedule for the U.S. contributions to ITER first plasma construction were finalized in January 2017 and detailed in the *Project Execution Plan for the U.S. Contributions to ITER Subproject-1*.[38] The DOE execution plan was developed by the U.S. DOE Office of Science based upon the Updated Long-Term Schedule (ULTS) to first plasma. The ULTS was approved by the ITER Council in June 2016 and independently reviewed by an ITER Council Review Group (ICRG) in April 2016.[39] As the committee notes, a measure of the reliability of ITER's new schedule is the fact that two years after the creation of the updated long-term schedule, the project remains on schedule for first plasma in 2025 and, since January 2016, has achieved all 33 scheduled project milestones.

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[37] Report of the FESAC Subcommittee on *Transformative Enabling Capabilities Toward Fusion Energy* (February 2018); available online at https://science.energy.gov/~/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf

[38] DOE, *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, Office of Science, Fusion Energy Sciences, Washington, D.C., January 2017.

[39] ITER Council Working Group on the *Independent Review of the Updated Long-Term Schedule and Human Resources* (ICRG), (15 April 2016); available online http://www.firefusionpower.org/ITER_ICRG_Report_2016.pdf.

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Fusion energy science is an active research area as evident from the significant number of scientific and technical publications. Since the 2004 report of the NAS Burning Plasma Assessment Committee, over 1,200 scientific publications have appeared authored or co-authored by scientists supported by the U.S. Department of Energy and reporting advancements in magnetic fusion research. As noted in the committee's Interim Report, the Nuclear Fusion Award has been given annually since 2006, and 8 of the 12 Nuclear Fusion Awards were presented to U.S. scientists working on scenarios, transport, stability, transient control, boundary, and pedestal physics. U.S. award recipients are Tim Luce (2006 General Atomics), Todd Evans (2008 General Atomics), Steve Sabbagh (2009 Columbia University), John Rice (2010 MIT), Pat Diamond (2012 University of California, San Diego), Dennis Whyte (2013 MIT), Phil Snyder (2014 General Atomics), and Rob Goldston (2015 Princeton University). The significant fraction of all articles published in magnetic fusion energy research are authored or co-authored by United States researchers. This included publication of the 'Progress in the ITER Physics Basis' (PIPB) comprehensive document authored by the international community in 2007.[1]

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F

Summary of Input Received from the Fusion Community

The magnetic fusion community in the United States has provided numerous assessments of research progress, opportunity, and strategy. The 2001 report of the NAS Fusion Science Assessment Committee[1] was informed by the two-week community Fusion Summer Study held in Snowmass, Colorado, July 20-23, 1999. The 2004 report of the NAS Burning Plasma Assessment Committee[2] was informed by a second Fusion Summer Study also held in Snowmass, Colorado, July 8-19, 2002.[3] The 2008 report of the NAS Committee to Review U.S. Fusion Community Participation in the ITER Program was informed by a community process organized by the U.S. Burning Plasma Organization.[4] The 2007 report of the FESAC subcommittee for Priorities, Gaps and Opportunities towards a Long-Range Strategic Plan for Magnetic Fusion Energy[5] was followed by a U.S. DOE sponsored workshop report prepared with input from more than two hundred fusion scientists assembled to define and characterize the research activities that advance fusion as a practical source of energy.[6] The most recent U.S. DOE Office of Science *Ten-Year Perspective* on the fusion energy sciences program prepared for Congress was informed by the reports from four community workshops: *Plasma Materials Interactions (2015), Integrated Simulations for Magnetic Fusion Energy Sciences (2015), Transients (2015),* and *Frontiers of Plasma Science (2017)*.[7]

Like these previous research planning efforts, the committee also benefited from community and expert input. Input from the fusion community was provided in three ways: (*i*) white papers and comments contributed through direct online submission to the NRC, (*ii*) technical presentations to the committee during seven open public meetings, and (*iii*) summary reports from two week-long community workshops: July 24-28, 2017 held at the University of Wisconsin at Madison, WI and December 11-15, 2017 hosted by the University of Texas at Austin, TX. All of these presentations were made public. Appendix B lists the technical presentations to the committee during open public meetings. A list of those presentations contributed through online submission and as a result of the community workshops are provided at the end of this appendix.

The input resulting from the community workshops, titled "U.S. Magnetic Fusion Research Strategic Directions,"[8] deserve special mention. The goals of the workshops were to discuss, debate, and develop critical technical information required for the development of a strategic plan, including program

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[1] National Research Council. 2001. *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*. Washington, DC: The National Academies Press. https://doi.org/10.17226/9986.

[2] National Research Council. 2004. *Burning Plasma: Bringing a Star to Earth*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10816.

[3] Information on the Fusion Summer Studies are online at https://fire.pppl.gov/snowmass02.html.

[4] U.S. Burning Plasma Organization, *Planning for U.S. Fusion Community Participation in the ITER Program*, June, 2006. https://www.burningplasma.org/resources/ref/fp/EPAct_final_June09.pdf

[5] U.S. FESAC Report of *Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy*, November 2007, https://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf

[6] U.S. DOE Office of Science, *Research Needs for Magnetic Fusion Energy Sciences*, June 8-12, 2009, https://science.energy.gov/~/media/fes/pdf/workshop-reports/Res_needs_mag_fusion_report_june_2009.pdf

[7] All four community workshop reports are available online from: https://science.energy.gov/fes/community-resources/workshop-reports/.

[8] See online website for community workshops on U.S. Magnetic Fusion Research (MFR) Strategic Directions, https://sites.google.com/site/usmfrstrategicdirections/home

mission and goals, and to present and discuss opportunities to achieve those goals through the pursuit of various scientific and technical programs. These workshops were highly successful and involved hundreds of researchers across the country. Workshop participants prepared detailed technical reports on nine strategic research program elements, descriptions of various strategic approaches to fusion research planning, and summaries of important working group topics such as the impact of ITER access to U.S. fusion scientists and the requirements for attractive fusion power systems. These technical descriptions underwent an informal peer review and described strategic elements of a U.S. fusion research program responding to the committee's task.

In a letter to the committee from the workshop co-chairs, reported, "over 200 members of the community have participated in this activity so far, submitting white papers and debating technical initiatives, missions, research pathways, and strategic principles in working groups and in two week-long workshops." U.S. researchers engaged in constructive debate of many of the challenging technical and strategic issues under study by the committee. While the workshop participants documented several strategic elements in technical white papers, the workshop co-chairs noted "a sustained effort well beyond the time horizon of your panel will be necessary for us to reach community consensus on key aspects of a strategic plan for the U.S. program." The technical descriptions for each strategic element were prepared by knowledgeable experts and updated to accommodate review comments. The committee is grateful for the considerable effort by white paper authors and their intent to inform rather than to advocate and to convey, as far as possible, a broader view of the U.S. research community's strategic directions activity.

These papers have been posted for a period of time on a public web site: https://sites.google.com/site/usmfrstrategicdirections/strategic-element-white-papers

SUMMARY OF PUBLIC INPUT PRESENTATIONS TO THE COMMITTEE

Presentations to the Committee

Meeting 1 - Washington, D.C.

- *Perspectives on Burning Plasma Research* – Chuck Greenfield, Amanda Hubbard, United States Burning Plasma Organization
- *Context for an NAS Study on Burning Plasma Research and A Magnetic Fusion Strategy* - Edumund Synakowski, DOE Office of Science

Meeting 2 - Irvine, California

- *Perspectives from the University Fusion Association* - David Maurer, Auburn University
- *A Reinvigorated U.S. Fusion Energy Program* - Stewart Prager, Princeton University
- *Perspective on Fusion Energy Strategy* - Tony S. Taylor, General Atomics
- *Perspectives from the US ITER Projec*t - Ned Sauthoff, US ITER Project Office
- *Response to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research* - Phil Ferguson, US Virtual Laboratory for Technology (VLT)

Meeting 3 - Austin, Texas

- *Further Context for NAS Burning Plasma Study* - James W. Van Dam, DOE Office of Science
- *The Road Not Taken -- Yet* - D. Whyte, MIT Plasma Science and Fusion Center
- *Strategic Plan for U.S. Burning Plasma Research* - R.J. Hawryluk and M.C. Zarrnstoff, PPPL

Meeting 4 - ITER, France

- *ITER Engineering Science and Breakthroughs* - Gyung-Su Lee, ITER
- *ITER: The Way to a New, Clean, Safe, and Near-Unlimited Energy* - Bernard Bigot, ITER
- *ITER Project Management* - Hans H. Altfeld, ITER
- *The Science of ITER* - Tim Luce, ITER

- *EU DEMO Design and R&D Activities: Progress and Updates* - Gianfranco Federici, EUROFusion

Meeting 5 - General Atomics, San Diego

- *Challenges and Strategy for Development of FNST: Blanket/FW & Tritium Fuel Cycle* – Mohamed Abdou, UCLA
- *On TAE's Path to Fusion: A Private-Sector Perspective* – Michl Binderbauer, TAE Technologies
- *A Mission to Discover the Plasma Solutions for Future Fusion Reactors* - RJ Buttery, General Atomics
- *General Atomics Perspective on the Strategic Plans for U.S. Fusion Energy Development* - David Hill, General Atomics
- *Perspective on Magnetic Fusion Energy Directions from Early Career Fusion Scientists* - Multiple Perspectives
- *Korean Fusion Energy Development Strategy* - Y.S. Hwang, Center for Advanced Research in Fusion Reactor Engineering
- *Chinese Fusion Energy Strategy* - J. Li, Institute of Plasma Physics
- *Research and Development Policy on Fusion Energy in Japan* - Yuichi Ogawa, The University of Tokyo
- *A Fusion Program Strategy for Timely Fusion Energy Development* - Mickey Wade, General Atomics

Teleconference - Stellerators (March 23, 2018)

- *U.S. Research on International Stellarators* - Samuel A. Lazerson, Princeton Plasma Physics Laboratory
- *A Vision for an Experimental Stellarator Program in the U.S. that is a Slingshot for a Stellerator D-T Device* - Oliver Schmitz et al

Meeting 6 - Princeton Plasma Physics Laboratory (April 11-13, 2018)

- *First-Wall, Plasma-Material Interaction, Liquid Metals, and Strategic Elements for Advancing Liquid Metal Science and Technology* - M.A. Jaworski, Princeton Plasma Physics Laboratory
- *A New Approach to Funding, Accelerating, and Commercializing Fusion* - R. Mumgaard, Commonwealth Fusion Systems
- *Magnetic Confinement-Based Fusion Research in the United States* - Soren Prestemon, Lawrence Berkeley National Laboratory
- *Plasma-Materials and Divertor Options for Fusion* - J. Rapp, Oak Ridge National Laboratory
- *SPARC: A Critical Step on the High-Magnetic-Field Path to Practical Fusion Energy* - Martin Greenwald, Commonwealth Fusion Systems
- *Long-term Fusion Vision, Strategy, and Role* - M.C. Zarnstorff, Princeton Plasma Physics Laboratory
- *Trying for Upside Potential in Controlling Fusion* - Nat Fisch, Princeton University
- *Advanced Scientific Computing Strategy for Fusion* - Amitava Bhattacharjee, Princeton Plasma Physics Laboratory
- *NSTX-U: An Essential Science Facility for US Fusion Innovation* - S. Gerhardt, Princeton Plasma Physics Laboratory
- *Options and Strategy Towards Fusion Net Electricity* - Jonathan Menard, Princeton Plasma Physics Laboratory

Public Input

Strategic Element White Papers - US Magnetic Fusion Research Strategic Directions

- *Letter to the Committee* - Hutch Neilson, Mickey Wade, Dave Maurer on behalf of the Magnetic Fusion Research Strategic Directions Activity
- *Entering the Burning Plasma Frontier,* Chuck Greenfield, Dale Meade, Chuck Kessel
- *Developing HTS Magnets for Fusion Applications,* Joe Minervini, Yuhu Zhai, Xiaorong Wang, Robert Duckworth
- *Magnetic Configuration Research: A Foundation Element for the Development of Magnetic Fusion Energy,* John Sarff, Uri Shumlak
- *Quasi-Symmetric Stellarators as a Strategic Element in the US Fusion Energy Research Plan,* David Gates, David Anderson, Dave Maurer, Chris Hegna
- *Importance of Theory, Computation, and Predictive Modeling in the US Magnetic Fusion Energy Strategic Plan,* Fatima Ebrahimi, Gary Staebler, Paul Bonoli, François Waelbroeck, Chris Hegna
- *Elements of a US R&D Plan to Solve Plasma-Material Interaction Challenges for Magnetic Fusion Energy,* Brian LaBombard, Peter Stangeby, Dick Majeski, Jean Paul Allain
- *Elements of a US R&D Plan to Develop Fusion Nuclear Materials,* Steve Zinkle, Yutai Katoh, Richard Nygren
- *Tritium Fuel Cycle,* Chuck Kessel, Arnie Lumsdaine
- *Sustained High Performance Tokamak as the Leading Magnetic Fusion Path to Net Electricity Production,* Richard Buttery, Steve Sabbagh, Earl Marmar

Strategic Approach White Papers

- *Use Present Physics and Technology Basis for DEMO* - Working Group for Strategic Approach 1 for the 2017 U.S. Magnetic Fusion Research Strategic Directions Workshops, S. Zinkle, W. Solomon, D. Newman
- *Delivering Key Technical Achievements, then DEMO* - Working Group for Strategic Approach 2 for the 2017 U.S. Magnetic Fusion Research Strategic Directions Workshops, G. Navratil, C. Collins, N. Howard

Working and Discussion Group White Papers - US Magnetic Fusion Research Strategic Directions

- Whitepaper on *Principles, Values, Metrics and Criteria for the Development of Magnetic Fusion Energy* - Working Group 1, Laila El-Guebaly, Lauren Garrison, Robert Goldston, Martin Greenwald, Walter Guttenfelder, Scott Hsu, Hantao Ji, Ilon Joseph, Karsten McCollam, Brad Merrill, Craig Michoski, Hutch Neilson, Francesca Turco.
- Whitepaper on *Technical and Programmatic Access to ITER*, Working Group 2.
- Whitepaper on *Fusion Market Attractiveness,* Working Group 3, David Hatch, Scott Hsu, and Mark Tillack (Co-chairs).
- Whitepaper *Summary of the Quasi-Symmetric Stellarator Program* - Working Group 4 for the Austin USMFR
- Discussion Group 5 Summary of USMFRSD Workshop in Austin, TX (January 12, 2018) - D. Sutherland et. al

Contributed White Papers

- *Plasma Pinch* (Physics World) - John E. Allen, University of Oxford
- *Two Comments on the NAS Interim Report on a Strategy Plan of U.S. Burning Plasma Research* - Stephen E. Bodner, (Ret.) Navy Research Laboratory
- *Whitepaper on Proposed Strategic Element for U.S. Magnetic Fusion Research* - M. R. Brown, B. Chapman, H. Gota, S. C. Hsu, R. Majeski, H. McLean, B. A. Nelson, U. Shumlak
- *The Advanced Tokamak Path to a Compact Fusion Power Plant* – R.J. Buttery, et. al, General Atomics

- *Comments on A Strategic Plan for U.S. Burning Plasma Research* - F.F. Chen, Professor Emeritus, University of California, Los Angeles
- *DOE Should Strongly Support Physics Research and Technology Development for Advanced-Fuel FRCs* - S.A. Cohen, Princeton Plasma Physics Laboratory
- *Brief Words on U.S. Fusion Research* - Clesio Ismerio de Oliveira, Eletrobras CGTEE
- *Historical Perspective on the United States Fusion Program* - Stephen O. Dean, Fusion Power Associates
- *Pilot Plant: A Shortened Path to Fusion Power* - Stephen Dean et. al, Fusion Power Associates, ORNL, MIT, Canadian Fusion Fuels Technology Project, Ebasco Services, Kurchatov Institute of Atomic Energy
- *Essential Criteria for Fusion Power Plants* - Laila El-Guebaly (UW-Madison), Ilon Joseph (LLNL), Brad Merrill (Idaho National Laboratory), Scott Hsu (LANL)
- *Worldwide Timelines for Fusion Energy* - Laila El-Guebaly, University of Wisconsin, Madison
- *Stellarator Research Opportunities* - National Stellarator Coordinating Committee
- Whitepaper on Proposed Strategic Element for U.S. Magnetic Fusion Research: *Opportunities Presented by Magneto-Inertial Fusion* - Scott Hsu et al.
- *The High-Field Path to Practical Fusion Energy* - M. Greenwald et. al, Massachusetts Institute of Technology Plasma Science and Fusion Center
- *Fusion Research: Time to Set a New Path* - Robert L. Hirsch, (Ret.) Science Applications International Corporation
- *Revamping Fusion Research* - Robert L. Hirsch, (Ret.) Science Applications International Corporation
- *A Tritium Research Program in Support of Burning Plasma Science and Fusion Energy* - P. W. Humrickhouse et. al, Idaho National Laboratory
- *The ITER Power Amplification Myth* - Steven B. Krivit, New Energy Times
- *Harsh Environment Microwave Diagnostics for Reactor Plasmas* - N.C. Luhmann, Jr et al.
- *Letter to the Strategic Plan for U.S. Burning Plasma Committee* - Shigekazu Matsuura, International Nuclear and Fusion Energy Affairs Division, Japan
- *Letter to Co-Chairs for Strategic Plan for U.S. Burning Plasma Committee* - Bruno Coppi, Ignitor Program
- *Letter to the Strategic Plan for U.S. Burning Plasma Committee* - Matthew Reinke, Oak Ridge National Laboratory
- *Letter to the Academy of Sciences on Fusion Review* - Walter L. Sadowski, (Ret.) Office of Fusion Energy Sciences, DOE
- *Letter to NAS* - Bruno Coppi
- *Collection of Documents by the University Fusion Association* - sent by David A. Maurer, University Fusion Association
- *Burning Plasma Physics and the U.S. Strategic Plan for Magnetic Fusion Energy* - Dale Meade, Princeton Plasma Physics Laboratory
- *A Vision for Attaining and Exploring a Burning Plasma for Attractive Fusion Power* - Dale Meade
- *A New Tandem Mirror Concept with High Fusion Power Gain* - T.C. Simonen and R.W. Moir, LLNL, Vallecitos Molten Salt Research
- *White Paper on Magnetic Fusion Program* - Weston M. Stacey, Georgia Institute of Technology
- *Be Bold: An Alternative Plan for Fusion Research* - G.A. Wurden, Los Alamos National Laboratory
- *Perspective on Magnetic Fusion Energy Directions from Early Career Fusion Scientists* - Multiple Authors

- *Follow-Up Polling of the Early Career Fusion Scientist Community in Response to NAS Panel Feedback* - Chris Holland et al.
- *ITER is a Showcase for the Drawbacks of Fusion Energy* - Daniel Jaasby
- *MIT's Nuclear Cure-Alls* - Daniel Jassby
- *Tritium Breeding Strategy for Advanced Fusion Power Plants* - L.A. El-Guebaly
- *Reshaping the Fusion Radwaste Management Approach* - L. A. El-Guebaly et al.
- *Important Gaps in the ST and AT Programs* - Roger Raman
- *Comments on the Interim Report* - S.A. Cohen
- *White Paper on U.S. Domestic Tokamak Program* - C.M. Greenfield, D.N. Hill, M.R. Wade
- *Accelerating Fusion Through Integrated Whole Device Modeling* - Amitava Bhattacharjee et al.
- *Development of a Steady State Fusion Core: The Advanced Tokamak Path* - R J Buttery et al., General Atomics, LLNL, ORNL, Oak Ridge Associated Universities
- *Sustained High Performance Tokamak as the Leading Magnetic Fusion Path to Net Electricity Production* - R.J. Buttery et al.
- A*ccelerated Compact Fusion Development and Innovations Leveraging Spherical Tokamaks* - Steven Sabbagh, Columbia University
- *A U.S. Strategic Plan for Timely Fusion Energy Development* - M.R. Wade, General Atomics
- *Need For 14 MeV Neutrons* - Mohamed Abdou
- *Pre-FNSF Research and Development*, C.E. Kessel, Princeton Plasma Physics Laboratory
- *The Fusion Nuclear Science Facility (FNSF) is a Critical Step Before Proceeding to Larger and Electricity Producing Fusion Plants* - C.E. Kessel, Princeton Plasma Physics Laboratory
- *Producing Electricity in a Fusion Nuclear Science Facility or Similar* - C.E. Kessel, Princeton Plasma Physics Laboratory
- *A Brief Historical Summary of Fusion Alternatives* - Charles W. Hartman, Harry McLean, Uri Shumlak
- *Why Fusion?* - Robert J. Goldston, Princeton Plasma Physics Laboratory
- *A Mid-Scale Quasi-Helically Symmetric Experiment Would Significantly Accelerate Fusion Development Through the Stellarator Line* - D.T. Anderson et. al, University of Wisconsin-Madison

G

Major Research Facilities of the United States and Other Nations

This appendix briefly describes major research facilities within the United States and of other nations. These facilities include: the DIII-D facility (San Diego, CA), NSTX-U (Princeton Plasma Physics Laboratory), smaller U.S. confinement research facilities, and the larger devices in Europe and Asia. All fusion research experiments with superconducting magnets are located outside the United States: EAST (China), KSTAR (ROK), WEST (formerly Tore Supra, located in France), Large Helical Device (LHD, located in Japan), and Wendelstein 7-X (Germany). The JT-60SA superconducting experiment is under construction in Japan and operation is expected to begin shortly after 2020. Recently, Italy announced intention to design and construct the superconducting Divertor Tokamak Test Facility (DTT).

DIII-D

DIII-D[1,2] is a medium-sized tokamak at conventional aspect ratio ($R/a \geq 2.5$) that is the largest magnetic fusion research experiment in the U.S. It is a multi-institutional user facility whose primary research goal is to:

- Provide solutions to physics and operational issues critical to the success of ITER,
- Develop the physics basis for steady-state tokamak operation required for efficient power production,
- Contribute substantially to the technical basis for a fusion nuclear science facility, and
- Advance the fundamental understanding and predictive capability of fusion science.

The DIII-D project commenced in 1986, and its technical capabilities have continually evolved so that DIII-D is presently a flexible device that can study confinement, stability and divertor physics with a variety of heating and current drive techniques. This, in turn, allows for the development of the high-performance, advanced tokamak concept, which requires targeted simultaneous control of multiple plasma profiles both in the plasma core and at the edge. Near-term research on DIII-D addresses the development of plasma scenarios scalable to the high fusion gain ITER target. Longer-term research focuses on developing techniques to produce stable, high-performance, steady-state (i.e., non-inductive) operation for ITER and beyond.

DIII-D has a major and minor radius of 1.67 and 0.67 m respectively, with a nominal aspect ratio of 2.5. It has a maximum operating capacity of 2.2 T toroidal magnetic field and 3 MA plasma current, although it generally operates at lower currents, ≤2 MA. Eighteen field-shaping coils operated by a plasma control system provide great flexibility in plasma shape, discharge evolution, and divertor configuration. Divertor cryopumps control the plasma density. DIII-D presently has 26 MW of external heating capability, split between 20 MW of neutral beam (NB) heating and 6 MW of electron cyclotron (EC) heating and current drive. The neutral beams are configured on and off-axis, and in the co- and counter-current direction to provide a range of torque and neutral beam driven non-inductive current profiles. Another key feature of DIII-D is the set of internal and external coils that can provide a wide spectral range of applied 3D magnetic perturbations for edge-localized mode (ELM) suppression and

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[1] Buttery, R., et al., Nucl. Fusion 55 104017 (2015)

[2] Solomon, W., et al., Nucl. Fusion 57 102018 (2017)

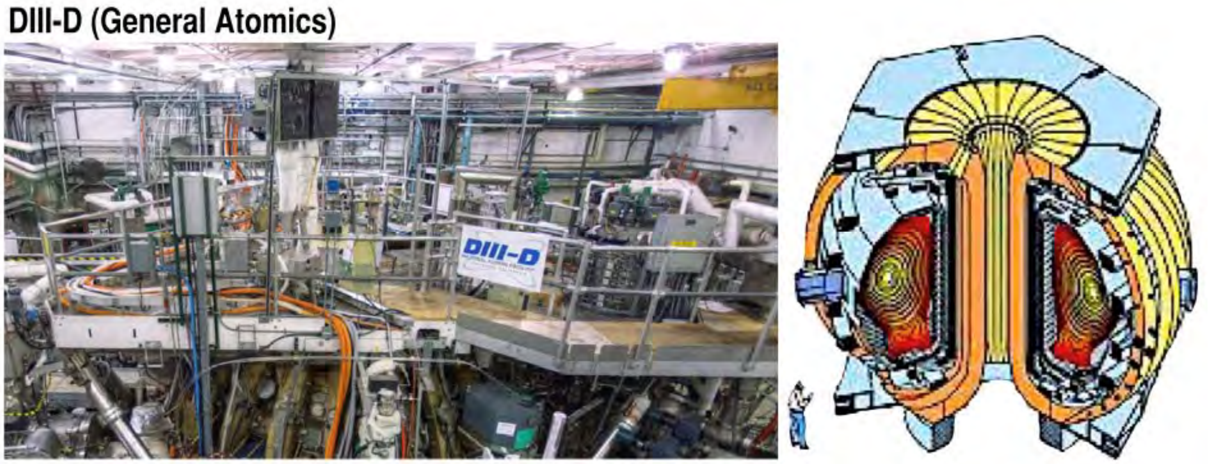

FIGURE G.1 The DIII-D National Fusion Facility, operated by General Atomics for the Department of Energy, is the largest magnetic fusion experiment in the United States. See http://www.ga.com/diii-d-national-fusion-facility-begins-transformation-to-prepare-for-future-reactors

other edge profile control studies. Shattered pellet injection and argon pellet systems are employed for disruption and runaway electron mitigation, a lithium and boron “dropper” is used for wall-conditioning, and a laser blow-off instrument is available for impurity transport studies. DIII-D has an outstanding, comprehensive set of core, edge and divertor diagnostics. A close relation between Theory and Experiment enables the data to be readily used to validate first-principles physics simulations for the development of high-confidence predictive tools.

A few examples from the diverse, multi-faceted research program are given below.

In ITER, unmitigated ELMs will rapidly erode first-wall materials. DIII-D was the first tokamak to use 3D magnetic perturbations to suppress ELMs. Design of the ITER 3D coils relied heavily on DIII-D results. In support of developing operational scenarios for ITER, many recent experiments explore stability and confinement in plasmas with low injected torque, and with significant electron heating, as is expected in ITER. In particular, validation of transport models against ITER baseline discharges in DIII-D have revealed the importance of certain drift-wave modes that cause particle transport into the center of the plasma. This model[3], when used to simulate ITER scenarios, predicts a peaking of the density profile, which is a necessary condition for achieving the $Q = 10$ ITER target[4]. Electron cyclotron heating was shown to be effective in expelling impurities from the core of these plasmas[5].

Demonstration of non-inductive scenarios with high confinement is another major program element. Experiments in the “hybrid” operational regime have achieved a normalized pressure of $\beta_N = 3.7$ with a confinement enhancement factor of 1.6 and zero loop voltage, indicating that a significant portion of the plasma current was self-driven[6].

Divertor and plasma-material solutions are key for a successful fusion reactor. A recent upgrade to the upper divertor module allowed DIII-D to study the physics of the small angle slot (SAS) configuration. This configuration can cause the divertor to radiatively “detach” from the hot upstream

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[3] Staebler, F.M. et al., Phys. Plasmas 12 102508 (2005)

[4] Grierson, B., et al., Phys. Plasmas 25 022509 (2018)

[5] Unterberg, E.A., et al., “Characterization of divertor tungsten sourcing and transport into the SOL and core for DIII-D ELMy H-mode conditions”, submitted to Nucl. Fusion (2017)

[6] Turco, F., et al., Phys. Plasmas. 22 056113 (2015)

plasma at lower densities, giving lower temperatures across the divertor region, and presents a potential divertor solution to mitigate high heat fluxes. In materials studies, tungsten inserts installed during a metal-rings campaign provided measurements of tungsten erosion, migration, and redeposition.

The DIII-D program emphasizes scientific understanding to develop a predictive capability that improves fusion performance. A model was developed that explains the observed height and width of the pressure "pedestal" at the plasma edge when the tokamak operates in the "H-mode" confinement regime[7,8]. Further analysis suggested that, by judicious choice of the plasma shape and discharge evolution, access to a higher pressure "super H-mode" was possible. Subsequent experiments accessed this higher performance regime, and produced plasmas with equivalent Q_{DT} of up to 0.6.

Modifications of DIII-D are currently underway. A major goal is demonstration of a steady-state condition with high confinement and pressure. To drive more off-axis current, one neutral beamline is being reoriented to inject off-axis. New methods to use plasma waves to drive current off-axis are also being prepared, including installation of a high-power helicon antenna.

Organizationally, DIII-D is managed by a private company, General Atomics (GA). Multiple national-laboratory and universities, as well as GA employees, constitute the scientific staff. Generally, GA employees operate the major systems, with several major subsystems the responsibility of national laboratory teams; diagnostic systems are the responsibility of university, national laboratory, and GA personnel. Experiments are selected after a "Research Opportunities Forum" that is open to all, review by a "Research Council" with experienced team members from GA, laboratories, and universities, and final allocations by GA management. Experiments are conducted by multi-institutional teams that often include international visitors. The research program is influential. As a measure of impact, consider the papers selected for oral presentations at the most recent IAEA Fusion Energy Conference (the highest visibility conference in the field). Of 42 experimental magnetic fusion papers, 15 utilized DIII-D data, the most of any facility in the world.

NSTX-U

The National Spherical Torus Experiment – Upgrade (NSTX-U)[9] is one of 17 tokamaks designed to operate in the low aspect ratio regime. It is a high-powered, medium-sized device that is one of the two largest and most capable low aspect ratio tokamaks in the world, the other being MAST-U[10] in the U.K. The mission of NSTX-U is to:

- Advance the spherical tokamak (ST)[11] as a candidate for a Fusion Nuclear Science Facility (FNSF)
- Develop solutions for the plasma-material interface, including the snowflake divertor and lithium/liquid metal plasma facing components (PFCs)
- Advance toroidal confinement physics predictive capability for ITER and beyond
- Develop the ST for fusion energy production, for example as an ST Pilot Plant.

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[7] Snyder, P.B., et al., Phys. Plasmas 16 056118 (2009)

[8] Snyder, P., et al., Nucl. Fusion 51 103016 (2011)

[9] Menard, J.E., et al., Nucl. Fusion 52 083015 (2012)

[10] Morris A.W. IEEE Trans. Plasma Sci. 40 682 (2012)

[11] Peng, M. and D. Strickler, Nucl. Fusion 26 769 (1986)

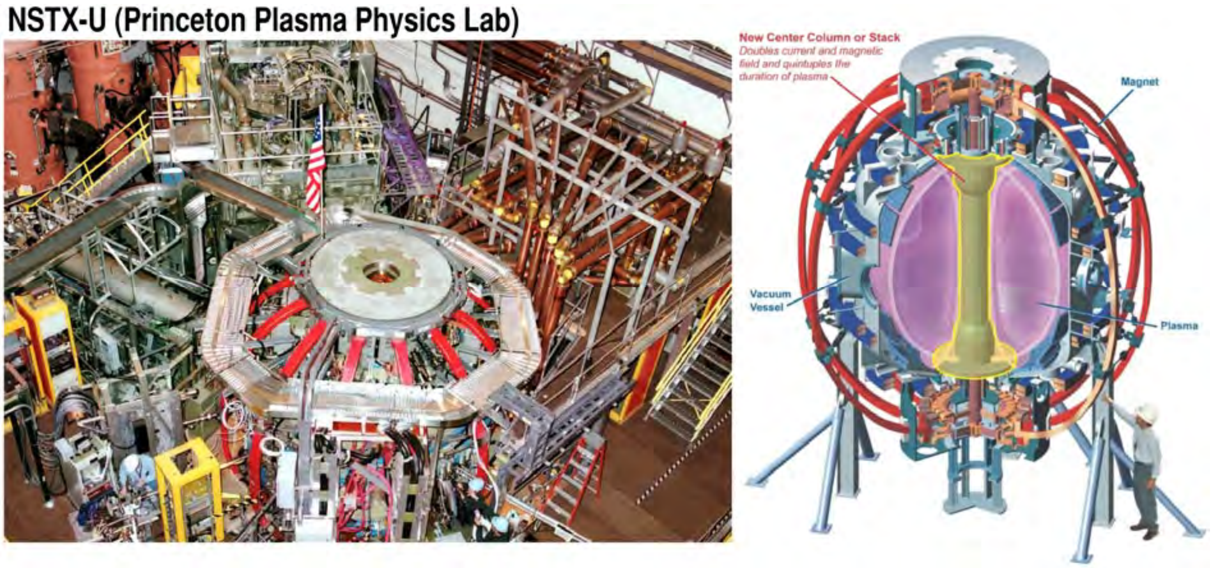

FIGURE G.2 The U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) runs the National Spherical Torus Experiment Upgrade (NSTX-U), which has undergone an upgrade allowing experimental tests of high-performance plasma under conditions of extreme heat and power. See https://www.pppl.gov/nstx.

The ST concept, in which $R/a \leq 2$, offers a potential development path for a more compact and lower-cost energy production system and/or materials testing facility through optimization of the fusion triple product $nT\tau$, where n is density, T is temperature and τ is energy confinement time. In particular, improvements in energy confinement are inherent in the ST due to the stabilizing properties of its high toroidicity, high plasma flow velocities and high flow shear. STs also naturally achieve high-β due to operation at lower toroidal magnetic field, and the spherical nature of the plasma configuration leads to high natural elongation. Also because of the low toroidal field, the fast ion population that results from neutral beam injection in STs resides in a parameter space expected for α-heated plasmas at both conventional and low aspect ratio. These unique physics regimes, along with the compact nature of the ST, which leads to stringent requirements for developing power handling and non-inductive current drive capabilities, offers great leverage in testing tokamak physics models for improved predictive capability.

Many of the ST physics challenges were explored in NSTX[12,13], the predecessor device to NSTX-U. NSTX had an aspect ratio of R/a=0.85/0.68~1.25, operated with plasma currents and toroidal magnetic fields of up to 1.5 MA and 0.55 T respectively, had pulse lengths of up to 1.5 sec, and operated in either D^+ of He^{++}. NSTX was equipped with a three-source neutral beam capable of injecting 6 MW of D^0 power at 90 keV, and up to 6 MW of High Harmonic Fast Wave RF power for heating and current drive. Co-axial Helicity Injection (CHI) was used for non-inductive plasma startup. Close-fitting passive conductors, coupled with application of active control algorithms using applied 3D magnetic fields as actuators, were used to stabilize MHD instabilities and maintain high-performance operations.

NSTX made significant progress in achieving a goal of high-β, long-pulse performance, including the achieving β_T values up to 35%, with β_N up to 6.5 m-T-MA^{-1} and β_N/l_i, a metric for maximizing bootstrap current, to 14. Its accomplishments include[14]:

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[12] Ono, M., et al., Nucl. Fusion 40 557 (2000)

[13] Kaye, S.M., et al., Fusion Technology 36 16 (1999)

[14] Kaye, S.M., Chapter 11 in "Magnetic Fusion Energy: From Experiments to Power Plants", ed. By G.H. Neilson, Woodhead Series in Energy, No. 99, Elsevier, 2016

- Pulse lengths up to 1 s with 60 to 65% of the current being driven non-inductively by both bootstrap and neutral beam current drive H-mode operation with $\tau_E/\tau_{98y,2}$ values up to 1.5 and τ_E/τ_{89p} values over 2.
- Confinement trends showing that performance improved with decreasing collisionality in a nearly linearly inverse fashion (see Fig. 6).
- Impurity transport rates near predicted neoclassical values in turbulent L-mode plasmas.
- Identification and development of approaches to control neoclassical tearing modes and resistive wall modes.
- Observation of different classes of fast ion-induced MHD, with modes in the conventional Alfvén Eigenmode (AE) range of frequencies (tens of kHz), but also with frequencies of 0.5-1 MHz, near the ion cyclotron frequency.
- Significant electron heating ($T_{e0} > 6$ keV) and indications of current drive with HHFW.
- Noninductive startup currents of up to 400 kA using CHI.
- Utilization of advanced divertor configurations (e.g., snowflake) with partial detachment to mitigate divertor heat flux.
- Use of lithium wall coatings to improve plasma performance and mitigate ELMs.

Coupled with these experimental achievements was the development of the theoretical underpinnings necessary for understanding the results. For instance, first-principles gyrokinetic simulations identified the microtearing mode, which is electromagnetic in nature and exists at high-β, as the microinstability responsible for most of the energy loss from the plasma, which was through the electron channel[15]. This mode becomes more stable as collisionality is reduced, consistent with the strong increase of global confinement time with decreasing collisionality. Theory development related to the fast ion-driven AE modes led to a deeper understanding of how these instabilities affect both the fast ion and thermal populations[16]. This understanding led to the development of models of fast ion transport that have been applied successfully at low and conventional aspect ratio. Furthermore, development of the theory of kinetic stabilization of Resistive Wall Modes in NSTX[17] was found to also explain stability trends at conventional aspect ratio.

NSTX-U will continue to explore physics issues critical to both low aspect ratio, but with enhanced capabilities. The toroidal magnetic field will be increased from 0.55 to 1 T, the plasma current from 1.5 to 2 MA, and the pulse length from 1 to 5 sec. A second, more tangentially injecting neutral beam was added, doubling the total available power up to 12 MW under normal operating conditions. These additions make NSTX-U the most powerful ST in the world, with the highest toroidal field and highest accessible pressure and β. This will allow NSTX-U to achieve up to ten times higher fusion triple produce (nTτ) and four times higher divertor heat fluxes, reaching levels expected in ITER.

The increased current, field and power will enable NSTX-U to operate at higher temperature and up to five times lower collisionality than in NSTX. Operation at reduced collisionality is critical to resolving how confinement varies with this parameter. If the favorable confinement trend with collisionality continues at these lower values, in contrast to the weaker dependence of confinement on collisionality at conventional aspect ratio, this would certainly be critical information for optimizing the ultimate design of a tokamak reactor, and would present the low aspect ratio, high-β regime as a potentially attractive one for a compact, more attractive reactor.

NSTX-U is an excellent test-bed for simulating α-particle physics applicable to burning plasmas and ITER. Neutral beam-heated NSTX-U plasmas will operate in the largest fast ion dynamic range of

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[15] Guttenfelder, W., et al., Nucl. Fusion 53 093022 (2013)

[16] Podesta, M., et al., Plasma Phys. Cont. Fusion 56 055003 (2014)

[17] Berkery, J.W., et al., Phys. Plasmas 17 082504 (2010)

parameter space of any ST or conventional aspect ratio tokamaks, and in the regime expected for α-heated plasmas at both low and higher aspect ratio (see Fig. 7). Experiments on NSTX-U have already shown the flexibility of the more tangential neutral beam in being able to phase space engineer the fast ion distribution in pitch angle and deposition profile in order to control the fast-ion instabilities[18].

NSTX-U will be the leader in assessing whether high-performance STs can be sustained without a transformer, a critical research component since the compact nature of an ST-based Pilot Plant, for instance, will preclude a substantial OH transformer. The flexibility of the more tangential neutral beam will allow for additional non-inductive current with profiles that can be controlled actively. Beam torque will induce rotation, and both active and passive stabilization of global MHD modes through the passive conducting plate and applied 3D magnetic fields, along with production of favorable current profiles, will allow sustainment of high performance. Additional non-inductive current will be produced by the plasma through the bootstrap effect, which can be optimized through the high β_N/l_i that will be attained, and which could be twice as high as that produced on NSTX. Predictive simulations indicate that 100% non-inductive operation at 1 MA is possible.

While there is significant overlap between the two major ST devices, NSTX-U will focus on core physics, and in a complementary fashion MAST-U will focus on boundary physics. MAST-U is equipped with a significant number of PF coils that will allow for much more flexible, long-legged divertor configurations than those that can be produced in NSTX-U. However, NSTX-U can contribute and, in some instances, lead in power exhaust studies. NSTX-U will be using solid lithium coatings to protect PFCs from high heat fluxes, to improve confinement and to suppress ELMs, as was done in NSTX. Solid lithium injectors on both the top and bottom of the vessel will serve to double the lithium deposition over that in NSTX. Long-term plans include the development of liquid metal divertors as a possible transformative wall solution.

NSTX-U operated for ten weeks in 2016 and had a productive scientific campaign. However, by the end of that period, it was discovered that one of the PF coils failed, necessitating NSTX-U to shut down for an extended Recovery outage. The NSTX-U Recovery is ongoing, with numerous design improvements, including modification of the vacuum chamber, in order to support flexible operations and increase reliability to achieve key mission goals. New requirements for the divertor heat fluxes have been defined, based on recent SOL heat flux width models. New halo currents loads have been determined based on data from NSTX, NSTX-U, MAST and conventional aspect ratio devices. New error field analysis has been conducted, with the goal of optimizing both the global MHD stability and minimizing PFC heat flux asymmetries for scenarios with large poloidal flux expansion. New designs of graphite plasma facing components utilize castellations to reduce the mechanical stresses, allowing tiles to reach surface temperature limits, ~1600 C. Improved divertor coil designs simplify fabrication and facilitate turn-to-turn testing. The NSTX-U Recovery project is on track to enhance reliability and safety and provide the highest performance ST device as a robust user facility. NSTX-U is expected to resume operations during CY2020.

Smaller Confinement Research Facilities within the United States

Pegasus is an ultra-low aspect ratio tokamak at the Univ. of Wisconsin that operates with R~0.35 m, R/a~1.13 – 1.3 B_T=0.17 T and elongation ~ 2. Its mission is to explore very high-β confinement and stability, and to develop non-inductive discharge start-up techniques. Pegasus has achieved β_T values near 100%, and it has also achieved H-mode plasmas, with threshold powers for accessing the H-mode well above (~15x) that predicted for the Pegasus operating parameters[19,20]. Localized DC helicity injection

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[18] Fredrickson, E.D., et al., Phys. Rev. Lett. 118 265001 (2017)

[19] Thome, K., et al., Phys. Rev. Lett. 116 175001 (2016)

[20] Thome, K., et al., Nucl. Fusion 57 022018 (2017)

utilizing plasma guns has produced induction-free plasmas with plasma currents up to 100 kA with the plasma current scaling with injected edge current in accordance with the Taylor relaxation mechanism[21].

LTX-β is also a low aspect ratio tokamak which is situated at Princeton Plasma Physics Laboratory, Princeton University, with R=40 cm, R/a~1.55, $B_T \leq 0.17$ T and $I_p \leq 100$ kA that is the follow-on device to LTX. The purpose of LTX-β is to develop the approach to using liquid lithium walls, and to study their effect on plasma performance. LTX used lithium coatings on a high-Z wall, and it exhibited flat electron temperature profiles and enhanced confinement without having the lithium dilute the core plasma or radiate power[22]. LTX-β will extend the capabilities of LTX with 700 kW of neutral beam heating and fueling, 100 kW of ECH/EBW for electron heating, higher B_T and I_p, longer pulse length, and upgraded diagnostics.

The Madison Symmetric Torus (MST)[23] at the University of Wisconsin is a reversed-field pinch (RFP) physics experiment, which relies on a transient burst of current to create the plasma and the confining magnetic fields. In the RFP, the toroidal magnetic field is weaker than the poloidal magnetic field, and it actually reverses direction in the plasma near the edge. The mission of MST, presently a formal User Facility, is to study fusion and astrophysical implications of reconnection[24], turbulence[25] and dynamo formation. A 1 MW neutral beam injector will be used to heat the plasma and enable studies of fast particles and their role in the reconnection process. A wide range of diagnostics is available for characterizing the plasma.

HSX[26], also at the University of Wisconsin, is a quasi-helically symmetric (QHS) stellarator with R=1.2 m, a=0.15 m and B_T up to 1.25 T. It has up to 200 kW of EC heating, which can heat the electrons up to 2 to 2.5 keV in the core. By nature of its QHS design, neoclassical electron thermal transport was reduced[27]. Furthermore, HSX exhibited reduced damping of plasma flow[28], important for ulitmately reducing turbulence-driven transport, reduced bootstrap and Pfirsch-Schlüter currents for maintaining plasma stability[29], and good particle confinement of transpped high-energy electrons[30]. HSX also serves as a flexible divertor test platform, able to produce either an island or non-resonant divertor.

HIDRA (Hybrid Illinois Device for Research and Applications) at the University of Illinois is a classical stellarator with R=0.72 m and a=0.19 m, with magnetic fields up to 0.5 T. The main focus of HIDRA is to study plasma-material interactions, including liquid lithium science and technology[31].

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[21] Bongard, M., et al., “Non-solenoidal injection on the Pegasus Spherical Tokamak”, https://www.researchgate.net/publication/318987686 (2017)

[22] Boyle, D., et al., Phys. Rev. Lett. 119 015001 (2017)

[23] Dexter, R.N., et al., Fusion Technology 19 131 (1991)

[24] Fridstrom, R., et al., Phys. Plasmas 23 062504 (2016)

[25] Williams, Z.R., et al., Phys. Plasmas 24 122309 (2017)

[26] Anderson, D., et al., Fusion Technology 27 273 (1995)

[27] Canik, J.M., et al., Phys. Rev. Lett. 98 085002 (2007)

[28] Gerhardt, S.P., et al., Phys. Rev. Lett. 94 105002 (2005)

[29] Schmitt, J.C., et al., Phys. Plasmas 21 092518 (2014)

[30] Anderson, D.T., et al., Fusion Sci. and Technology 50 171 (2006)

[31] Andruczyk, D., et al., Fusion Sci. and Technology 68 497 (2017)

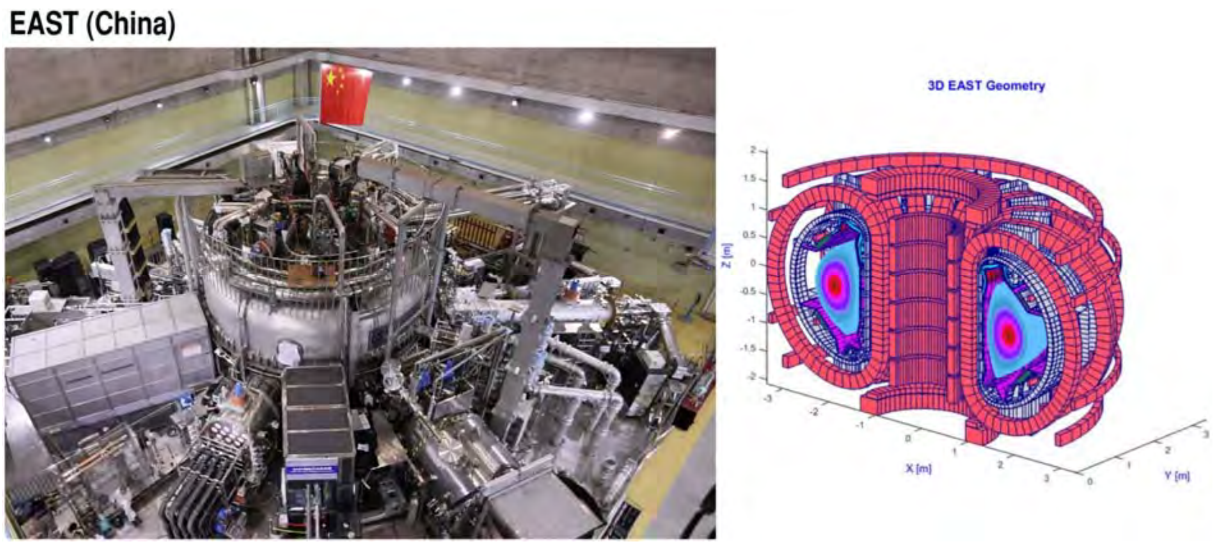

FIGURE G.3 Experimental Advanced Superconducting Tokamak (EAST) is a superconducting tokamak demonstrating high-fusion confinement performance in steady-state. EAST has a major radius of 1.8 m, and the EAST superconducting magnets are energized to 320 MJ. See http://english.ipp.cas.cn/rh/east/.

The Compact Toroidal Hybrid (CTH)[32] device at Auburn University is designed to study how MHD stability in a stellarator depends on 3D shaping of the plasma. It has R=0.75 m, a=0.29 m, B_T=0.7 T, and it has independently controlled magnet coils that can produce magnetic configurations over a large range of vacuum transforms, as well as having additional coils to control plasma shape as well as horizontal and vertical position. There is an ohmic system that produces plasma current, and when operated in this mode, disruptions due to vertical displacement events, density limits and low-q have been observed[33].

The mission of the HBT-EP[34] device at Columbia University is to utilize an adjustable close-fitting conducting wall for passive stabilization[35], and applied external magnetic perturbations[36] for active control of MHD modes to study and extend the β-limit. It has R=0.92 m, a=0.15 m and B_T=0.35 T.

The Helimac[37] is an R=1 m, B_T=0.1T is a toroidal device that is used to study plasma turbulence at high collisionality[38]. Because its magnetic field lines have low pitch, its geometry approximates that of an infinite cylinder. Flow shear is externally applied and can be controlled. The plasma is colder, with T_e ~10 eV and densities of only 10^{17} m^3.

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[32] Hartwell, C.J., et al., Fusion Sci. and Technology 72 76 (2017)

[33] Pandya, M.D., et al., Phys. Plasmas 22 110702 (2015)

[34] Sanhar, M.K.V., et al., J. Fusion Technology 12 303 (1993)

[35] Levesque, J.P., et al., Phys. Plasmas 22 056102 (2015)

[36] Rath, N., et al., Nucl. Fusion 53 073052 (2013)

[37] Zimmerman, E.D. and S.C. Luckhardt, J. Fusion Energy 12 289 (1993)

[38] Rowan, W.L. et al., Pulsed Power Plasma Science, IEEE Conf. Abstracts (2001)

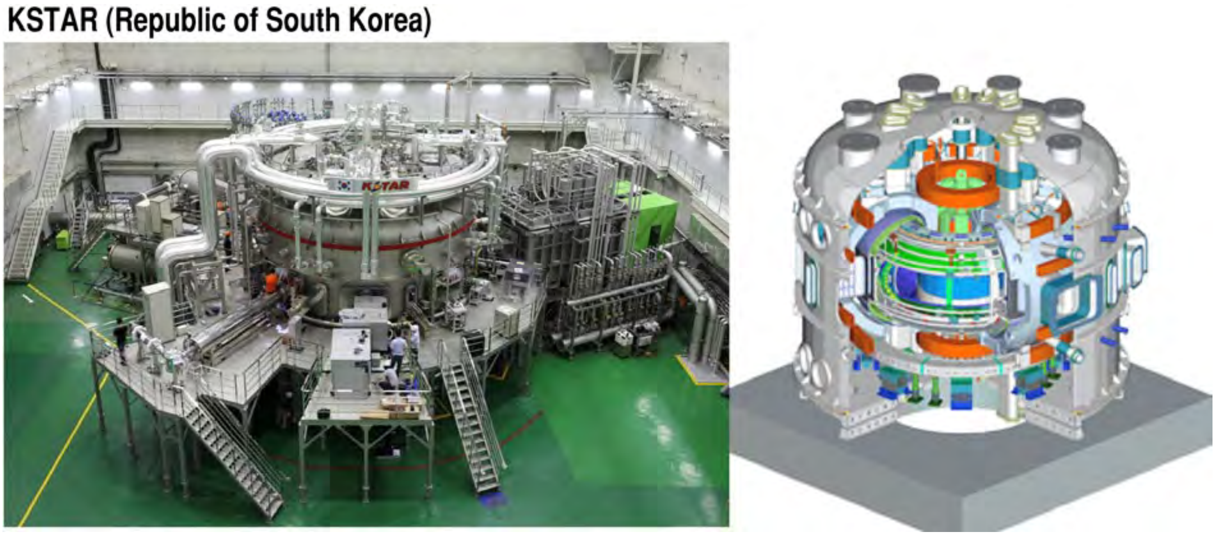

FIGURE G.4 KSTAR is a superconducting magnetic fusion experiment at the National Fusion Research Institute in Daejeon, South Korea. KSTAR has a major radius of 1.8 m and superconducting magnets energized to 450 MJ. See https://www.nfri.re.kr/eng/pageView/74.

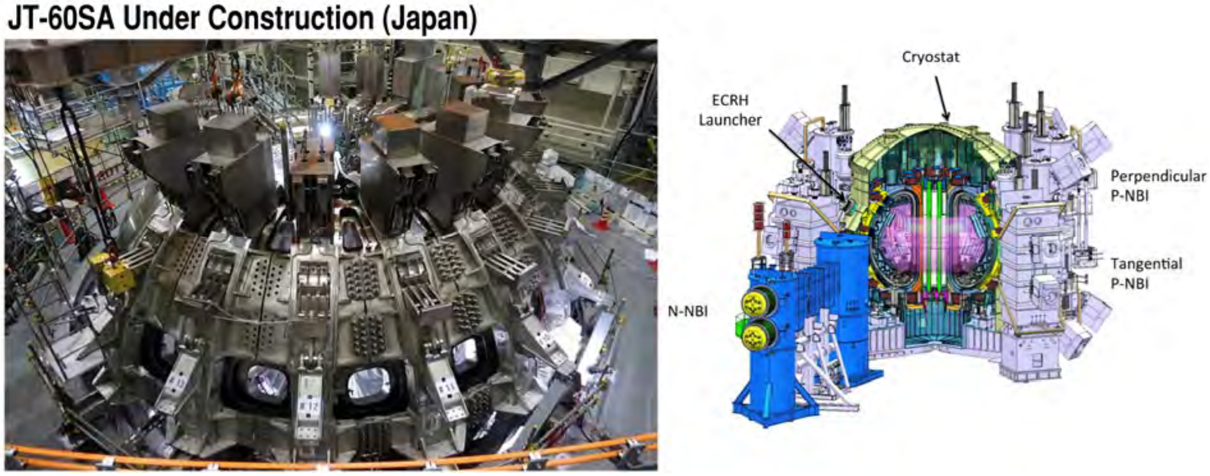

FIGURE G.5 JT60-SA is a joint international research project, involving Japan and Europe, and under construction in Naka, Japan. This is an upgrade of the JT-60 experiment. SA stands for "super, advanced", and will study advanced modes of plasma operation. http://www.jt60sa.org/b/index.htm.

International Fusion Research Facilities

The current U.S. fusion research strategy has an increasing focus on U.S. participation in newer international long-pulse experiments with superconducting magnets including EAST (China)[39], KSTAR

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[39] Wu, S., et al., Fusion Eng. and Design 82 463 (2007)

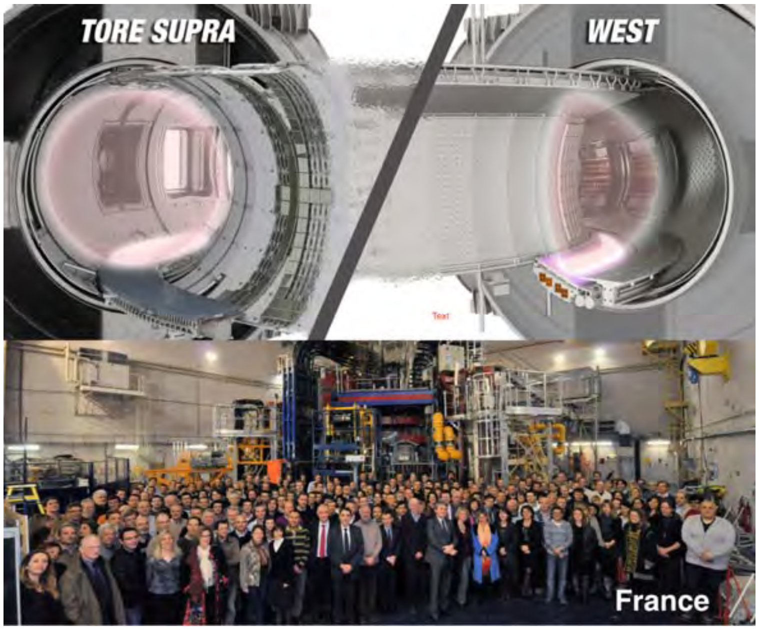

FIGURE G.6 WEST is an upgrade of the former Tore Supra superconducting tokamak located at the CEA Cadarache Center in France. WEST achieved divertor operation with a tungsten first wall in 2018. See http://west.cea.fr/en/index.php.

(Republic of Korea)[40], and Wendelstein 7-X (Germany)[41]. EAST began operation in 2006 and KSTAR began in 2009. The Wendelstein 7-X stellarator began operation in December 2015, requiring €350 million for the stellarator device[42] and additional amounts for personnel and materials during construction. The HL-2M tokamak is under construction at the Southwestern Institute of Physics[43] as an upgrade to the existing HL-2A[44] device. HL-2M will have higher plasma heating power and magnetic field strength to explore higher-pressure, fusion-relevant plasma. The JT-60SA tokamak in Japan is under construction as a Japan-Europe project and is expected to begin operation in 2020[45]. Non-U.S. proposals for new facilities include the superconducting Divertor Tokamak Test facility[46] that would be built by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development's fusion laboratory in Frascati, Italy, and the China Fusion Engineering Test Reactor (CFETR) under consideration as a new fusion facility to demonstrate self-sufficient tritium breeding. While researchers in the U.S. fusion community welcome these international opportunities, presentations to the committee[47] and during the first fusion community workshop[48] did not foresee how international cooperation by itself will allow the U.S. fusion researchers to maintain a world leadership position without new facility starts within the United States.

The United States has made and continues to make important contributions to the world's largest currently operating fusion device, Joint European Tours (JET). This includes involvement in testing important auxiliary systems relevant to ITER (e.g., the ITER-like Shattered Pellet Injector[49]), plasma diagnostics (e.g., Faraday cups), and experimental operating scenarios (e.g., involvement in developing

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[40] Oh, Y.-K., et al., Fusion Eng. and Design 84 344 (2009)

[41] Bosch, H.-S., et al., Nucl. Fusion 57 116015 (2017)

[42] see http://www.ipp.mpg.de/4010154/02_16

[43] Liu, D., et al., Fusion Eng. and Design 96-97 298 (2015)

[44] Duan, X., et al., Nucl. Fusion 57 102013 (2017)

[45] Shirai, H., et al., Fusion Eng. and Design 109 1701 (2016)

[46] Crisantia, F., et al., Nucl. Mat. and Energy 12 1330 (2017)

[47] See "A reinvigorated US fusion energy program," Stewart Prager, presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research (August 29, 2017)

[48] For example, "Perspectives on a Restructured US Fusion Energy Research Program," T. Carter, R. Fonck, M. Haynes, D. Maurer, D. Meade, G. Navratil, S. Prager, G. Tynan, D. Whyte, presented to the Workshop on U.S. Magnetic Fusion Research Strategic Directions (July 24, 2017)

[49] Baylor, L, et al., IEEE Trans Plasma Sci, 38 419 (2010)

deuterium-tritium scenarios[50]). Additionally, simulation codes (e.g., TRANSP[51]) developed by U.S. scientists have been adopted by international partners and are now routinely used for scenario modeling within the JET program and across EUROfusion ITER-related activities. Since 2016, 9 of the 33 articles appearing in the International Atomic Energy Agency (IAEA) journal Nuclear Fusion and reporting results from the JET device involved co-authors from the United States.

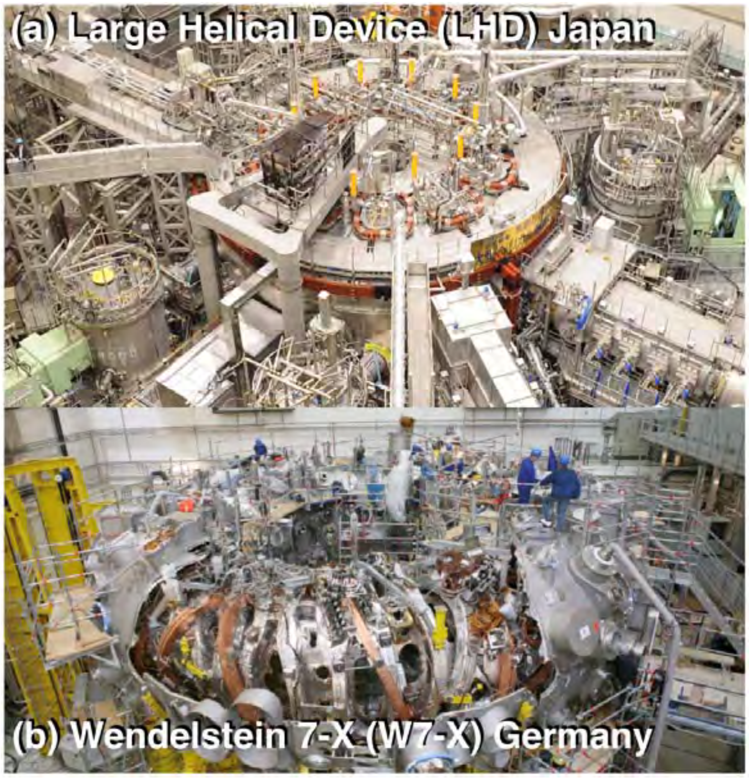

FIGURE G.7 Photographs of the world's two large superconducting stellarator experiments. LHD located in Japan has a major radius of 3.5 m, and the LHD magnets are energized to 900 MJ. W7-X is located in Germany, with a major radius of 5.5 m and superconducting magnets with 640 MJ.

For intermediate-sized tokamaks (ASDEX Upgrade, Germany; TCV, Switzerland; MAST Upgrade, United Kingdom), many bilateral collaborations exist between the United States and EU partners. Prominent recent examples of U.S. contributions include temporarily moving diagnostic devices from U.S. facilities to EU machines and joint experiments on multiple machines to develop understanding and robust demonstration of control schemes and new plasma scenarios. Since 2016, about 10 percent of the articles appearing in Nuclear Fusion describing research with these medium-sized tokamaks involved co- authors from the United States.

Another important U.S. contribution to fusion research in the EU has been the participation in the Wendelstein 7-X stellarator project. This includes the construction and operation of five large auxiliary coils[52] (installed on the outside of the device to assist in precise setting of the magnetic fields at the plasma edge) and an X-ray spectrometer, as well as the development of fluctuation diagnostics and a pellet injector. This work is carried out at three U.S. national laboratories (Princeton Plasma Physics Laboratory, Oak Ridge, and Los Alamos) and three U.S. universities (Auburn University, University Wisconsin–Madison, and Massachusetts Institute of Technology), supporting Wendelstein 7-X with equipment that has been funded, designed, and produced in the United States and with related magnetic field and plasma diagnosis and modeling. Since 2016, more than half of the articles appearing in Nuclear Fusion describing research with the Wendelstein 7-X stellarator involved co-authors from the United States.

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[50] Budny, R., et al., Nucl. Fusion 48 075005 (2008)

[51] Hawryluk, R., in An empirical approach to tokamak transport Physics of Plasmas Close to Thermonuclear Conditions: Proceedings Course (Varenna, Italy, 1979) vol 1, p 19 (1980)

[52] Lazerson, S., et al., Nucl. Fusion 57 046026 (2017)

The United States is actively playing a significant role in developing new fusion programs in Asia. Major contributions have been made to the programs on new Asian devices since the 2004 NRC report, notably in EAST (China), KSTAR (Republic of Korea), HL-2A (China), and J-TEXT (Japan), and a strong relationship continues with smaller spherical tokamaks (QUEST at Kyushu University, Japan; VEST at Seoul National University, Republic of Korea; SUNIST at Tsinghua University, China). In particular, non-inductive plasma startup and ramp-up using Co-axial Helicity Injection and Electron Cyclotron Wave Heating and Current Drive is the focus of a multi-domestic institution collaboration with QUEST. A major focus of this international partnership has been in the use of long-pulse superconducting devices to develop steady-state plasma scenarios.[53] As an example, collaborations on EAST have made advances in plasma control and wall conditioning techniques developed collaboratively with and initially demonstrated on DIII-D. Novel computer science hardware and software infrastructure has improved data movement, visualization, and communication and allow scientists in the United States to remotely conduct experiments using the EAST facility[54]. In July 2017, the Chinese researchers using EAST achieved a stable 101.2-second steady-state high confinement plasma, setting a world record in long-pulse H-mode operation[55]. Similarly, physicists at Princeton Plasma Physics Laboratory have connected remotely to run experiments on KSTAR.

Recent U.S.-Asia cooperation is also seen in the development of HL-2M under construction in China and in the physics design of CFETR burning plasma facility under consideration in China, where the United States provides design expertise and simulation codes[56].

International Collaboration in U.S. Research

International collaboration with U.S. researchers in burning plasma science involves all parts of the program, including use of experimental facilities and involvement with theory, simulation, and modeling groups. As a metric of international involvement since 2016, of those articles appearing in the IAEA journal Nuclear Fusion describing research with U.S. medium-sized tokamaks, one-fourth involved co-authors from Europe and one-fourth involved co-authors from Asia. Half of all articles appearing in Nuclear Fusion since 2016 reporting advancements in fusion simulation involved collaborating international co-authors. In the area of fusion technology and engineering science, the EUROfusion Work Package for Plasma Facing Components pays to use the PISCES-B facility at University of California, San Diego, helping to identify first wall materials for ITER and future fusion energy systems. Currently, no other linear plasma facility is capable of performing experiments with beryllium samples. One main goal of this collaboration is to study the interaction between deuterium or helium plasmas with beryllium and tungsten surfaces. Another example of a long-standing U.S.-Japan collaboration is the study of high dose irradiation effects in in an experiment on the High Flux Isotope Reactor at Oak Ridge National Laboratory.

International participation from Asia (China and Korea in particular) in the U.S. program also has the goal of importing established U.S. scientific knowledge such as 3D physics, tokamak scenario development, diagnostic techniques, Heating & Current Drive technology (ECH, Klystron for helicon CD, LHCD high field launch), advanced plasma control systems including real time control and tokamak design and construction (e.g., HL-2M design and construction was based on knowledge gained from DIII-D). Joint experiments such as those performed on EAST and DIII-D, simulation and modeling codes such as BOUT++, technology transfer on linear plasma source for PMI study such as PISCES are also areas where the current focus of the collaborating Asian scientists is to absorb leading scientific expertise of the U.S.

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[53] Garafalo, A., et al., Nucl. Fusion 57 076037 (2017)

[54] Schissel, D.P. et al., Nucl. Fusion 57 056032 (2017)

[55] See https://phys.org/news/2017-07-china-artificial-sun-world-steady-state.html

[56] Chen, J., et al., Plasma Phys. Cont. Fusion 59 075005 (2017)

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Schedule and Budget Implications

This appendix summarizes input examined by the committee regarding cost and schedule. These were used by the committee in its considerations of the budget implications of its recommended strategic plan for U.S. burning plasma research.

The committee examined estimates for the cost and schedule for the two main research activities: (*i*) construction and operation of the ITER burning plasma experiment and (*ii*) a national program of accompanying research and development leading to the construction of a compact fusion pilot plant. It also examined the schedule and budget implications of a decision by the United States to withdraw from the ITER project. Because the committee's long-term strategic guidance covered the next several decades, all cost and schedule estimates are necessarily notional. They were based on information and recommendations provided to the committee by way of previous studies. Implementation of the committee's strategic guidance and the development of budget estimates based on detailed facility designs and program missions will require significant planning and effort by the fusion research community, involvement with international partners, and oversight by the U.S. Department of Energy. Additionally, because the committee's strategic plan involves research and technology development over several decades, the impact of unanticipated discoveries, breakthroughs, or technical setbacks that would influence the schedule and cost of the strategic plan could not be determined.

Costs of U.S. Participation in the ITER Project

The project cost and schedule for the U.S. contributions to ITER first plasma construction were finalized in January 2017 and detailed in the *Project Execution Plan for the U.S. Contributions to ITER Subproject-1*.[1] This plan, when combined with the ITER cost and schedule information in the Secretary of Energy's Report to Congress in May 2016,[2] provides a basis for cost and schedule for the first main recommendation of the committee: to remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of power plant. This schedule was developed by the U.S. DOE Office of Science based upon the Updated Long-Term Schedule (ULTS) to first plasma. The ULTS was approved by the ITER Council in June 2016 and independently reviewed by an ITER Council Review Group (ICRG) in April 2016.[3] As the committee notes, a measure of the reliability of ITER's new schedule is the fact that two years after the creation of the updated long-term schedule, the project remains on schedule for first plasma in 2025 and, since January 2016, has achieved all 33 scheduled project milestones.

Consistent with the ULTS, the *ITER Research Plan (IRP)* was updated in September 2018 and describes the overall research activities for ITER during both the first, non-nuclear, operations and experimentation and the second, nuclear operations phase, using deuterium and tritium (DT).[4]

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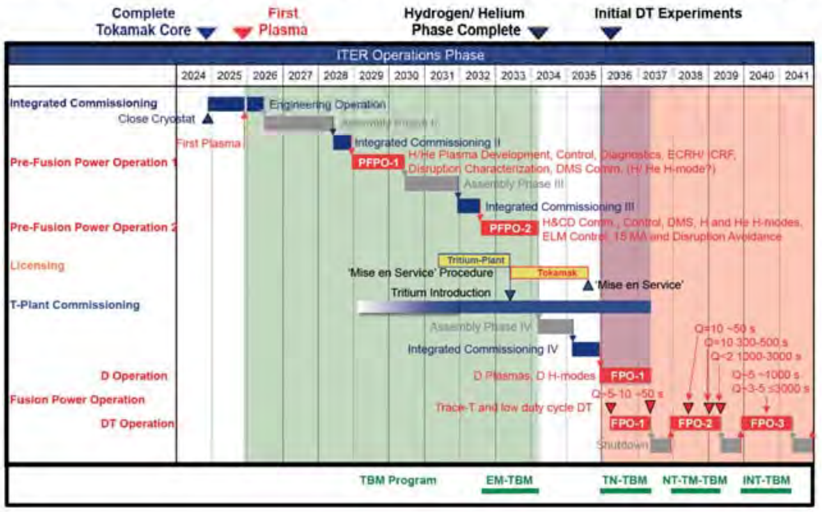
[1] DOE, *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, Office of Science, Fusion Energy Sciences, Washington, D.C., January 2017.

[2] U.S. Department of Energy, *U.S. Participation in the ITER Project*, Report to Congress, Washington, D.C., May 2016.

[3] ITER Council Working Group on the *Independent Review of the Updated Long-Term Schedule and Human Resources* (ICRG), (15 April 2016); available online [http://www.firefusionpower.org/ITER_ICRG_Report_2016.pdf].

[4] ITER Organization, *ITER Research Plan within the Staged Approach* (Report ITR-18-003; 17 September 2018)

(a) ITER Operations Plan within Staged Approach (from *ITER Research Plan within the Staged Approach* (Report ITR-18-003; 17 Sept 2018), Fig. 2.2-1, p. 38)



(b) Costs of U.S. Contributions to ITER (from U.S. DOE, *U.S. Participation in the ITER Project*, Report to Congress, May 2016, pp. 10-13)

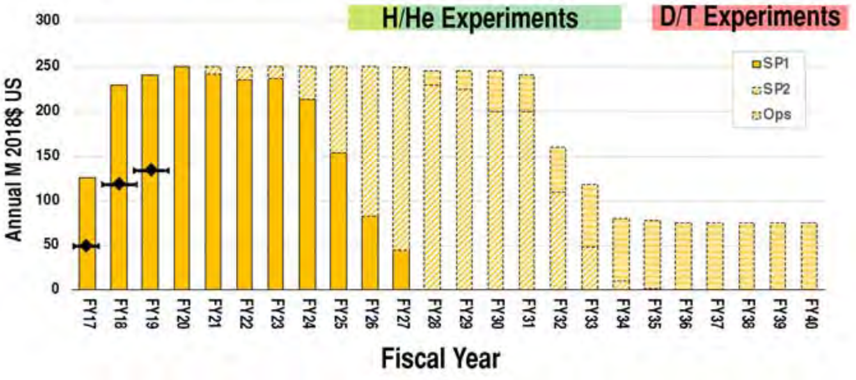


FIGURE H.1 Research and cost schedule for U.S. participation in the ITER Project. (a) The *ITER Research Plan* calls for operation in two phases: the non-nuclear hydrogen and helium phase (2026-2033) and the fusion nuclear phase using deuterium and tritium fuel (2036-2041). (b) The annual costs for U.S. contributions to ITER. These costs include SP-1 and SP-2 construction and contributions to operations and research. The FY17, FY18, and FY19 enacted funding levels for ITER are indicated with "◆".

The estimated the cost of construction, operation, and maintenance for U.S. continued partnership in the ITER Project was described in Section 4 (pp. 10-13) of the Secretary of Energy's Report to Congress delivered in May 2016.[2] Two cost and schedule estimates were presented, recognizing the uncertainty of the achievement of the first plasma milestone in 2025. If construction progress continues according to the updated long-term schedule (ULTS), first stage construction (Subproject-1, SP-1) will be completed in calendar year 2025. The total project cost for the U.S. will be minimum, but the peak annual funding will be $275M. If ITER construction proceeds more slowly than scheduled, first plasma will occur in 2028. In this case, the sum total U.S. construction cost would increase slightly (by $43M for the entire SP-1 construction project), but the peak annual funding would be lower, at $250M. According to the U.S. DOE Report, a late first-plasma date of 2028 is consistent with schedule contingency while maintaining the start of DT experiments in 2035. Construction costs include in-kind contributions of components and materials (*e.g.* the superconducting central solenoid, microwave and radio-frequency transmission lines, tokamak cooling water systems) and cash contributions to the ITER Organization (IO). Cash to the IO support essential tasks, including construction management, ITER research and development, on-site assembly and testing of all ITER components.

After completion of first-plasma construction, U.S. continues to provide in-kind and cash contributions for the "post-first-plasma" activities, called Subproject-2 (SP-2), leading to the commencement of burning plasma experiments with deuterium and tritium.

For the purposes of estimating the budget implications of its strategic guidance, the committee adopted the 2028 first plasma construction profile. Including both SP-1 and SP-2 estimated costs, the U.S. ITER funding profile requires annual funding at $250M for more than a decade.

Fig. H.1 shows both the most recent ITER research plan[4] and the estimated cost and schedule of U.S. contributions to ITER. The achievement of first plasma is a high-level technical achievement and will represent the successful operation of the world's largest superconducting magnet system. Non-nuclear experiments begin in the 2025-2028 time-frame, and DT fusion nuclear experiments begin in 2035. As detailed in the I*TER Research Plan*, important scientific and technical research will be accomplished in both the non-nuclear and nuclear phases.

After construction is completed and operations begin, the United States share of ITER operations increases from the 9.09% share of ITER construction to 13% of ITER operations. Using the ITER operating cost estimated in the ICRG Report, U.S. contributions to ITER operations will be approximately $40M. As an ITER member, the U.S. receives full access to all ITER research; however, the U.S. research program at the ITER facility will need to be funded through U.S. DOE/FES funds.

As indicated in Fig. H-1(b), present U.S. funding for ITER construction does not meet obligations. The FY2019 enacted budget provides $132M, and the annual costs for U.S. participation in ITER needs to increase by approximately $100M for more than a decade. Upon completion of ITER construction beginning FY2034, U.S. ITER annual research costs are expected to be $75M.

Costs of a National Program leading to Construction of a Compact Pilot Plant

While the cost and schedule for U.S. participation in ITER are well characterized, the cost and schedule of a national program of accompanying research and technology leading to the construction of a compact fusion pilot plant are not. As a consequence, the committee's cost and schedule estimates for this half of the program were based on examination of previous reports of U.S. burning plasma strategy and fusion development. Additional inputs from the fusion science and technology community, including definition of detailed program activities and facilities, are needed to elaborate these costs and schedules.

For the purposes of cost and schedule estimates, the committee considered five broad research categories: (*i*) national fusion energy science user facilities, (*ii*) fusion technology research, including materials research, high-field superconducting magnets, tritium science and technologies, and fusion nuclear science and components, (*iii*) discovery and innovation research in fusion science and technology, (*iv*) theory, modeling and predictive simulation, and (*v*) engineering studies and design activities for the compact pilot plant.

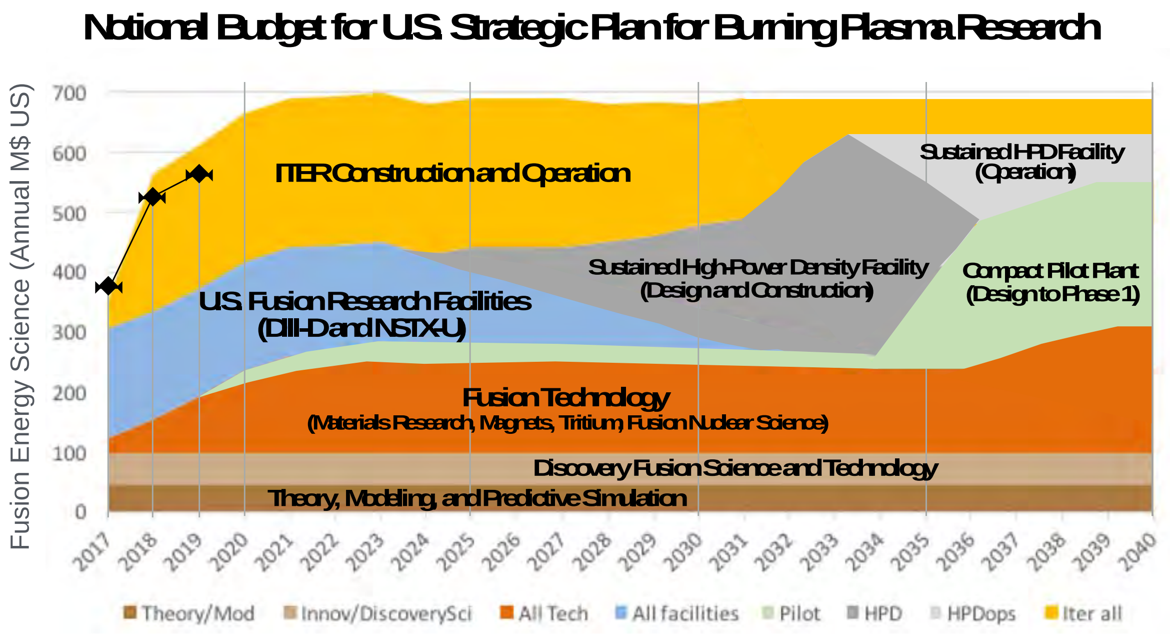


FIGURE H.2 Notional budget, in FY2018 dollars, implied by the committee’s strategic guidance for a national program of burning plasma research. The figure shows, in addition to the U.S. ITER costs, the evolution of five broad research categories: (*i*) national fusion user facilities, (*ii*) fusion technology research, (*iii*) discovery research in fusion science and technology, (*iv*) theory, modeling and predictive simulation, and (*v*) engineering studies and design activities for the compact pilot plant. The total U.S. DOE/FES funding levels for FY17, FY18, and FY19 are indicated with “◆”.

Fig. H-2 illustrates the committee’s notional cost and schedule implications for these five research categories along with the cost and schedule for U.S. participation in the ITER project. The graph shows an aggregated funding, and is provided to illustrate notional allocations. Any actual funding profile would be allocated after vetting, particularly with respect to the phasing in and out of the different facility contributions.

The DIII-D experiment (located at General Atomics, San Diego) and the NSTX-U experiment (located at the Princeton Plasma Physics Laboratory) are the two major research facilities presently supported by the U.S. DOE/FES as national user facilities. During the next decade, these facilities will be used to answer key scientific questions and will also develop promising operating scenarios in preparation for ITER experiments. Additionally, the committee’s strategic plan calls for these facilities to play an essential role beyond ITER, including optimizing the configurations that will demonstrate the science and technology for sustained operation at high-power density and informing the design for a next-step research facility. As explained in Ch. 5, the committee’s strategic guidance necessitates an evolution of major research facilities. The operation of the DIII-D and NSTX-U facilities will end, near completion of ITER construction, and allowing construction of a new national research facility to begin.

Three recent FESAC Reports provided cost estimates of facilities and programs that were considered by the committee. These are:

- Report of the FESAC Subcommittee on the *Prioritization of Proposed Scientific User Facilities* (March 2013) available online.[5] This report reported costing estimates for four facilities and upgrades: (*i*) a fusion materials irradiation facility, (*ii*) a fusion nuclear science facility, (*iii*) a quasi-symmetric stellarator facility, and (*iv*) upgrade to the DIII-D national fusion facility.
- Report of the FESAC Subcommittee on *Strategic Planning: Priorities Assessment and Budget Scenarios* (October 2014) available online.[6] This report describes a budget scenario having "modest growth" that results in additional funding, approximately $100M/annually, to non-ITER research that allows the start of a fusion nuclear science initiative and allows construction of a fusion neutron irradiation facility in collaboration with U.S. DOE/BES and a linear divertor simulator for plasma-materials interaction studies.
- Report of the FESAC Subcommittee on *Transformative Enabling Capabilities Toward Fusion Energy* (February 2018) available online.[7] This report describes several "revolutionary" ideas that would dramatically increase the rate of progress towards fusion power through increased fusion performance, device simplification, reduced cost or time to delivery, or improved reliability and/or safety. The committee's consideration for the budgetary implications of the strategic plan assume continued progress in the innovative technologies that lower the cost and fully enable fusion electricity.

In addition to the above mentioned FESAC Reports, the committee examined the budget estimates provided in the 2003 Report of the FESAC Subcommittee for a *Plan for the Development of Fusion Energy*,[8] the 2016 *U.S. Magnet Development Program Plan*[9] initiated by the DOE Office of Science and HEPAP, and the 1987 Report of the Office of Technology Assessment (OTA) *Starpower: The U.S. and the International Quest for Fusion Energy*,[10] which reported the cost of the Large Coil Task (p. 159) and serves as a model for similar superconducting research for new high-field superconducting magnets as discussed in Ch. 4.

As indicated in Fig. H-2, besides ITER construction and operation, the U.S. DOE needs to significantly expand the U.S. research program in fusion nuclear technology, advanced materials, safety, and tritium and blanket technologies to fully enable fusion energy. The committee estimates the U.S. fusion energy science research program will require an additional $100M/annually for this expanded fusion technology research. This increase is consistent with (*i*) the 2014 FESAC "modest growth" strategy that supports the start of a fusion nuclear science initiative including research on plasma-material studies with a linear divertor simulator, design and construction of a new materials neutron-irradiation facility that leverages existing neutron spallation source, and increased research on blanket technologies and tritium science, and (*ii*) the fusion materials testing program of the 2003 FESAC fusion development

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[5] Report of the FESAC Subcommittee on the *Prioritization of Proposed Scientific User Facilities* (March 2013); available online at https://science.energy.gov/~/media/fes/fesac/pdf/2013/FESAC_Facilities_Report_Final.pdf

[6] Report of the FESAC Subcommittee on *Strategic Planning: Priorities Assessment and Budget Scenarios* (October 2014); available online at https://science.energy.gov/~/media/fes/fesac/pdf/2014/October/FESAC_strategic_planning_rept_dec14.pdf

[7] Report of the FESAC Subcommittee on *Transformative Enabling Capabilities Toward Fusion Energy* (February 2018); available online at https://science.energy.gov/~/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf

[8] Report of the FESAC Fusion Development Panel (March 2003), A Plan for the Development of Fusion Energy, DOE/SC-0074; also available as Goldston, R., Abdou, M., Baker, C. et al. *Journal of Fusion Energy* (2002) 21: 61. https://doi.org/10.1023/A:1025038002187 .

[9] S. A. Gourlay, S. O. Prestemon, A. V. Zlobin, L. Cooley, D. Larbalestier, *The U.S. magnet development program plan*, Lawrence Berkeley Nat. Lab., Jun. 2016; available online http://www2.lbl.gov/LBL-Programs/atap/MagnetDevelopmentProgramPlan.pdf

[10] U.S. Congress, Office of Technology Assessment, *Starpower: The U.S. and the International Quest for Fusion Energy*, OTA-E-338 (Washington, DC: U.S. Government Printing Office, October 1987).

plan. The committee’s budget guidance emphasizes innovative technology research, careful-planning, and staged, cost-effective facility steps. A fusion component testing facility (sometimes also called a fusion nuclear science facility) is among the costliest facilities discussed in these previous reports. However, as described in the recent FESAC *Transformative Enabling Capabilities Toward Fusion Energy,* innovations are expected to lower cost of fusion technology development and testing. Additionally, schedule planning will occur as part of a staged research plan in the compact fusion pilot plant so that integrated testing of fusion blankets can be carried out as part of national user facility licensed for tritium operation.

An important addition to an expanded fusion technology program that was not previously described is the testing of large-bore, high-field HTS magnets for fusion. Ch. 4 presents the committee’s recommendation to demonstrate the ability to achieve high magnetic fields using high-critical temperature superconductors (HTS). A reference for this program is the Large Coil Task (LCT) which required about $94M (current dollars) with each superconducting test coil costing between $28M and $35M to construct. As was also described in Ch. 4, the expanded fusion technology research program would include advanced manufacturing, engineering systems studies, and research to enable advancements in heating, control, and diagnostics needed for the compact fusion pilot plant.

Fig. H-2 indicates one evolution for the major research facilities in the U.S. (i.e. the DIII-D and NSTX-U facilities). The operations of these facilities end prior to 2030, and construction of a new national research facility will begin to demonstrate the science and engineering needed to sustain a magnetically confined plasma having the high-confinement property and compatible plasma exhaust system that are needed for a compact fusion pilot-plant. Provided the U.S. remains an ITER partner, the research goal of this new national facility would be to address the divertor and first-wall issues for a compact pilot plant. It would a major, world-class research facility to resolve critical needs, but it would not be a fusion nuclear facility and would not involve those burning plasma science questions that require injection of tritium. Fig. H-2 indicates approximately $1.5B US for the design and construction of this facility. This construction cost was estimated in the 2003 *Plan for the Development of Fusion Energy* (p. 37) as $550M, comparable to the construction costs for the German superconducting stellarator experiment (Wendelstein 7-X)[11] and to the Italian-proposed Divertor Tokamak Test Facility (DTT).[12] Proposals provided to the committee from the U.S. fusion community for such a new research facility also considered approaches having reduced costs through the upgrade of some existing research capabilities from the two major fusion user facilities in the United States.[13]

Engineering systems studies for the compact fusion pilot plant would begin immediately in the U.S. strategic plan. These studies would identify science and technology areas for additional research and guide program decision. As shown in Fig. H.2, design activities for the compact fusion pilot plant would guide essential research for the next two decades and help coordinate progress in burning plasma science, fusion technologies, and the integrated science encompassing the divertor-pedestal-core needed for sustained high-power density magnetic confinement fusion.

The annual funding to implement the committee’s recommendation, including both continued participation in ITER and the start of a national research program for a compact pilot-plant, requires nearly $200M higher than currently enacted funding levels. About half of this additional amount is required to meet ITER commitments and the other half is needed to launch the science and technology supporting the research leading to a compact fusion pilot-plant. The budget profile after completion of

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[11] See “Wendelstein 7-X fusion device produces its first hydrogen plasma: Federal Chancellor switches plasma on / Start of scientific experimentation,” IPP Max-Planck-Institut für Plasmaphysik (February 3, 2016); available online at https://www.ipp.mpg.de/4010154/02_16

[12] *Divertor Tokamak Test facility - Project Proposal,* Italian National Agency for New Technologies, ENEA (ISBN: 978-88-8286-318-0; July 2015, ENEA Frascati Research Center, Italy); available at http://www.enea.it/it/pubblicazioni/pdf-volumi/V2015_TokamakProposal.pdf

[13] See, for example, Wade, M., (March 2018) *“A U.S. Strategic Plan for Timely Fusion Energy Development,”* White Paper submitted to the Committee and Buttery, R.J., *et al.*, (March 2018) “*Development of a Steady State Fusion Core – The Advanced Tokamak Path,*” White Paper submitted to the Committee.

ITER construction is uncertain and would need an evaluation based on progress in the national research program.

Fig. H.2 indicates the annual funding for the U.S. DOE/FES program for FY2017, FY2018, and FY2019. The FY2019 U.S. DOE/FES total funding is $564M, which is about $130M less than the annual funding estimates in Fig. H.2. However, the present U.S. DOE/FES program includes plasma science research, called discovery plasma science, totaling $84M in FY2019. This funding provides important support for non-fusion related research, including high energy density laboratory plasma physics, low-temperature plasma science, and fundamental plasma science. The committee's strategic guidance includes funding for discovery fusion science and technology and fusion theory, modeling, and predictive simulation, but the committee did not consider the funding priorities for the broad discipline of plasma science that extends beyond establishment of the science and technology needed to develop an economical source of fusion power.

Cost and Schedule Implications of a U.S. Decision to Withdraw from the ITER Project

As explained by the Secretary of Energy (p. ii of Ref. 2), "ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power." Because ITER is a major part of the U.S. fusion research program, a decision by the U.S. to withdraw from the ITER project, would significantly disrupt the national effort, isolate U.S. researchers from the international effort, and eliminate the benefit of sharing the cost of producing a burning plasma at the power plant scale. Without ITER participation, the United States would need to design, license, and construct an alternative means to gain experience creating and controlling an energy-producing burning plasma. Experience controlling and sustaining a burning plasma is needed as part of the continued U.S. strategy to design and construct a compact fusion pilot-plant in the long-term.

The committee was unable to estimate the cost and schedule of a research program comparable to that shown in Fig. H.2 for the scenario without ITER participation. Recent FESAC reports have not considered this scenario, and no details were provided to the committee from the research community.

The potential costs associated with a decision to withdraw from the ITER partnership was described by the Secretary of Energy's Report to Congress (p. 13 of Ref. 2). The Joint Implementation Agreement (JIA) for ITER requires the U.S. to continue to deliver or pay the remaining share of ITER construction costs, estimated to be about $2B. Additional project termination costs were estimated to total $66M.

As discussed in Ch. 5, in order to establish the science and technology basis for the compact fusion pilot plant, the previously-discussed high-power density experiment to establish the physics basis for continuous sustainment of high-power density burning plasma would need to be capable of operation with tritium fuel and designed for the burning plasma studies now envisioned for ITER. The construction and operation of this experiment would be expensive for the U.S. to undertake alone, but it would be critical for directly addressing the physics of a strongly-coupled burning plasma and reducing the key barriers for low-cost fusion energy development. For example, a fusion nuclear research facility, like the FSNF, was examined in the 2013 FESAC Report on *Prioritization of Proposed Scientific User Facilities*[5] (p. 13). Estimated total project cost for the FSNF is multi-billion dollars, and significant scientific and engineering challenges needed to be resolved before initiating construction. For this reason, the design and planning for a fusion nuclear facility to serve as an U.S. alternate to ITER would need to begin immediately. Considering the time that was required to design the ITER experiment and to develop pre-conceptual designs for the FNSF, the committee concludes the achievement of electricity production from fusion in the United States would be delayed significantly and the sum of both ITER termination obligations and the construction of a larger fusion research facility to study the physics and gain experience with the technology needed to control and sustain a burning plasma would be larger than the research program that benefits from the ITER partnership.

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Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research (National Academies of Sciences, Engineering, and Medicine, The National Academies Press, Washington, D.C., 2018) is reprinted here in its entirety. Note that the reprinted report's page numbers reflect the pagination that applies for inclusion in the current report, rather than the pages numbers of the original report.

INTERIM REPORT OF THE COMMITTEE ON A STRATEGIC PLAN FOR U.S. BURNING PLASMA RESEARCH

Committee on a Strategic Plan for U.S. Burning Plasma Research

Board on Physics and Astronomy

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A Consensus Study Report of
The National Academies of
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Preface

In January 2003, President George W. Bush announced that the United States would begin negotiations to join the International Thermonuclear Experimental Reactor (ITER) project and noted that “if successful, ITER would create the first fusion device capable of producing thermal energy comparable to the output of a power plant, making commercially viable fusion power available as soon as 2050.”[1] In 2007, the United States became an ITER member after signing a binding international agreement with China, the European Union, India, Japan, the Republic of Korea, and Russia. The United States and the other ITER members are now constructing ITER with the aim to demonstrate that magnetically confined plasmas can produce more fusion power than the power needed to sustain the plasma. This is a critical step towards producing and delivering electricity from fusion energy.

Since the international establishment of the ITER project, ITER’s construction schedule has slipped and ITER’s costs have increased significantly, leading to questions about whether the United States should continue its commitment to participate in ITER. These concerns resulted in a directive from Congress, appearing in the 2016 Consolidated Appropriations Act, that the Secretary of the Department of Energy (DOE) report to Congress on United States participation in the ITER project, including budget projections, project schedule, project management, and foreign policy implementations.

The Secretary’s report was delivered to Congress in May 2016 and recommended that the United States remain a partner in the ITER project through fiscal year (FY) 2018. The report acknowledged the significant construction progress made at ITER and the substantial improvements of ITER project management but also noted that significant technical and management risks remain. It remains to be seen whether the United States will continue its ITER membership beyond FY2018 as well as whether project performance will be sustained and the larger costs needed for U.S. obligations for ITER construction can be accommodated in future budgets for the DOE Office of Science. The Secretary’s report stated that, prior to the FY2019 budget submittal, “the U.S. re-evaluate its participation in the ITER project to assess if it remains in our best interests to continue our participation.”[2]

In addition to outlining various oversight and management reviews to ensure continued improvement in ITER project performance, the Secretary’s report requested advice from the National Academies “to perform a study of how to best advance the fusion energy sciences in the United States, given the developments in the field since the National Research Council study in 2004, the specific international investments in fusion science and technology, and the priorities for the next ten years developed by the community and the Office of Fusion Energy Sciences (FES) that were recently reported to Congress. This study will address the scientific justification and needs for strengthening the foundations for realizing fusion energy given a potential choice of U.S. participation or not in the ITER project, and will develop future scenarios in either case.”[3]

In response to this request, the National Academies of Sciences, Engineering, and Medicine established the Committee on a Strategic Plan for U.S. Burning Plasma Research. The committee’s statement of task is given in Appendix B.

The statement of task requests the preparation of this interim report prior to submission of strategic guidance that will be developed later and presented in a final report. Although the committee has not yet completed its work guiding the long-term fusion research strategies in both scenarios, in which the United States is, or is not, a member in ITER, the committee has completed its assessment of the current status of U.S. fusion research and of the importance of burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

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[1] George W. Bush: Fact Sheet: ITER, January 30, 2003. Available online by G. Peters and J.T. Woolley, The American Presidency Project, http://www.presidency.ucsb.edu1/ws/?pid=80124.

[2] U.S. Department of Energy, *U.S. Participation in the ITER Project*, Report to Congress, Washington, D.C., May 2016, p. ii.

[3] Ibid., p. 16.

This interim report is based on the information the committee received in its first two meetings (see Appendix C), from review of a large number of prior reports and studies, which includes DOE's Project Execution Plan for U.S. Contributions to ITER Subproject-1 released in January 2017 (see Appendix D), and from the first of two community workshops on strategic directions for U.S. magnetic fusion research held at the University of Wisconsin, Madison, from July 24 through July 28, 2017.

Having completed its assessment of the status and importance of U.S. burning plasma research, the committee anticipates that the final report will present strategies that incorporate continued progress toward a burning plasma experiment and a focus on innovation. The committee will receive input from the second community workshop on strategic directions for U.S. magnetic fusion research to be held at the University of Texas, Austin, December 11-15, 2017, and several site visits. Additionally, a subcommittee of the Fusion Energy Sciences Advisory Committee to the DOE Office of Science is expected to complete its report shortly, identifying the most promising transformative enabling capabilities for the United States to pursue that could promote efficient advance toward fusion energy.

To the extent possible, the committee's final report will include considerations of the health of fusion research sectors within the United States, the role of international collaboration in the pursuit of national fusion energy goals, the capability and prospects of private-sector ventures to advance fusion energy concepts and technologies, the impact of science and technology innovations, and the design of research strategies that may shorten the time and reduce the cost required to develop commercial fusion energy.

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

Roger D. Blandford, NAS,[1] Stanford University,
Richard Buttery, General Atomics,
James D. Callen, NAE,[2] University of Wisconsin, Madison (retired),
Steve Cowley, Corpus Christi College,
Robert Iotti, ARC Nuclear,
Johnathan E. Menard, Princeton University,
Ann White, Massachusetts Institute of Technology, and
Steven J. Zinkle, NAE, University of Tennessee, Knoxville.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Marcia J. Rieke, NAS, University of Arizona, and William Dorland, University of Maryland, College Park. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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[1] Member, National Academy of Sciences.
[2] Member, National Academy of Engineering.

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Summary

In this interim report, the Committee on a Strategic Plan for U.S. Burning Plasma Research makes the following assessments of the importance of burning plasma research to the development of fusion energy and of the current status of U.S. burning plasma research, including current and planned participation in international activities.

Assessment 1: Burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components.

All efforts to make fusion energy require a burning plasma—an ionized gas like the Sun and stars that is heated by fusion reactions. Burning plasma research begins with understanding, measuring, and predicting the complex physical processes of the plasma and of the energetic particles moving within the plasma created by fusion reactions. Next, burning plasma research includes the high-technology tools used to control, confine, and heat the plasma to very high temperature and pressure. Finally, burning plasma research embodies the applied and engineering sciences necessary to design reliable structures that surround the plasma and convert fusion energy into useful heat and power. Burning plasma research is interdisciplinary and results in technological and scientific achievements that touch many aspects of everyday life and lead to new insights in related fields such as optics, fluid mechanics, and astrophysics.

Although significant fusion power has been generated for short periods in the laboratory (4 MW for 4 s and up to 16 MW for shorter periods) and some processes expected in a burning plasma have been studied at the temperatures and pressures required for fusion energy, a burning plasma, which is heated predominately by fusion reactions, has never been created. This requires construction of a burning plasma experiment such as the International Thermonuclear Experimental Reactor (ITER). A burning plasma experiment will allow integrated investigation of the burning plasma with the advanced technology magnetic fusion schemes require. Because of its large size and complexity, constructing a burning plasma experiment leads to advancements in industrial capability, such as for large superconducting magnets, vacuum technologies, complex cryogenic systems, ultra-precise construction, and robotic systems to handle materials.

Assessment 2: The U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.

Experiments conducted using research facilities in the United States have been highly productive. New ideas to control and sustain burning plasma have been discovered, and theoretical and computational models developed in the United States have substantially improved the ability to control plasma stability, predict plasma confinement, and enhance fusion energy performance. The understanding of burning plasma science has advanced significantly, including such critical topics as the transport of heat and particles by multi-scale turbulence, the behavior of energetic particles produced by fusion reactions, and the physics of the narrow insulating layer at the plasma edge (or "pedestal"). In addition, new techniques have been developed to avoid and mitigate transient events, which can erode plasma facing materials. Scenarios of burning plasma operation that are expected to simultaneously satisfy the requirements for stability, confinement, fuel purity, and compatibility with plasma facing components have been developed experimentally and explored with computational models. These scenarios further increase confidence in the burning plasma performance that can be achieved in ITER. While important avenues for further exploration remain, current understanding increases confidence that ITER will achieve its scientific mission. The widely recognized importance of U.S. research contributions to the field also supports the expectation that, if the

United States continues to participate in ITER, scientists within the United States will make leading contributions to the study of fusion energy at the power plant scale.

Assessment 3: Construction and operation of a burning plasma experiment is a critical, but not sufficient, next step toward the realization of commercial fusion energy. In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.

A burning plasma experiment will examine for the first time many of the interconnected scientific and technology issues that must be addressed to produce magnetic fusion energy. Among these are the experimental validation of theoretical predictions related to plasma stability, plasma heating, transport of plasma heat and particles, alpha particle physics from fusion reactions, and disruption avoidance for tokamaks in substantially unexplored regimes of magnetic confinement. Equally important are gains in fusion engineering science including large-scale superconducting magnet technology, progress toward understanding fusion blanket science, tritium science and management, remote handling of materials and components, and large-scale systems integration. As a burning plasma experiment, ITER is a critical step along the path to advance the science and technology of a fusion power source.

Still, ITER is a fusion research facility and a long way from being a system for commercial power. In a commercial system, economics requires the thermal power to increase about seven-fold. Continuous operation requires efficient coupling of radio waves into the plasma to sustain the plasma current. Challenging plasma-wall problems need inventive solutions in order to safely handle the flux of energetic neutrons on the inner wall and the escaping heat from the plasma that is directed onto the plates of a protective divertor. The self-consistent production and safe handling of tritium will not be fully addressed in ITER but must be solved for commercial fusion power. Lastly, the expected gains in engineering and economics that might accrue from technology and materials innovations, like the newly developed rare-earth, high-temperature superconductors, need to be investigated; however, these innovations will only impact fusion facilities built beyond ITER. The overall picture is that a burning plasma experiment, such as ITER, will lead to major gains along the path to fusion energy while other fusion energy experiments will need to address remaining science and technology challenges and demonstrate innovative solutions that lead to a reduced size, lower cost, full-scale power source.

Assessment 4: Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.

Since the National Research Council's (NRC's) study in 2004,[1] strategic plans leading to a fusion energy demonstration have been developed by many of our international partners, all with high-level governmental support including, in some cases, accompanying legislation. These strategies all recognize that the burning plasma regime promised by ITER is the most expedient way to demonstrate controlled fusion on commercial scale and, importantly, elucidate the accompanying research and technology programs needed to progress beyond ITER to a commercial fusion reactor. Such strategic planning guides national research and innovation programs, helps to engage industrial partners, and sets the national priorities of our partners, enabling them to develop key areas of unique expertise. The absence of such a nationally endorsed strategic plan for delivery of fusion energy in the United States inhibits the long-term planning of all participants in the fusion endeavor in the United States, from universities, to national laboratories, to industrial partners. Without a long-term plan, the United States risks being overtaken as our partners advance the science and technology required to deliver fusion energy. Conversely, the adoption of such a plan has the potential to support strategic funding decisions and priorities within the national program and help foster innovation towards commercially viable fusion reactor designs.

Assessment 5: Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.

As reported by the 2004 NRC report,[2] many of the scientific and technical issues of importance to the long-range development of fusion are best addressed by research facilities having size and complexity much smaller than that needed for a burning plasma experiment. A long-term strategy for fusion energy benefits from a domestic effort

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[1] National Research Council (NRC), *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[2] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

in parallel with the ITER project focused on developing the scientific base for promising fusion reactor concepts and technologies.

However, during the past decade, various programmatic decisions have closed domestic experimental facilities without opportunities for new starts and without compensating programs internationally. In 2005, the budget for U.S. fusion technology efforts was sharply reduced. In 2013, the Department of Energy's (DOE's) Office of Fusion Energy Sciences implemented an overall reduction in the domestic program while making only a modest increase in funding for scientific collaborations on non-U.S. experimental facilities. Currently, only one mid-scale fusion experiment is operating in the United States. Mid-scale experimental facilities can attract talent to the field, provide broad scientific and engineering opportunities, and test innovations that could improve the fusion energy concept and strengthen U.S. expertise in fusion science and technology.

Assessment 6: Any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary for such an inherently large project. A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.

Past studies of magnetic fusion energy research recommended U.S. entrance into international partnerships as the most cost-effective approach to undertake large fusion energy experiments. These studies include *Cooperation and Competition on the Path to Fusion Energy*,[3] *Pacing the U.S. Magnetic Fusion Program*,[4] the 1995 President's Committee of Advisors on Science and Technology (PCAST) panel report *The U.S. Program of Fusion Research and Development*,[5] and *Realizing the Promise of Fusion Energy*.[6] After considering various options for a burning plasma experiment, the 2004 NRC report[7] recommended that the United States should participate in ITER. But, if the United States were not to participate in ITER, that committee also recommended the pursuit of international partnership in an alternate burning plasma experiment. A burning plasma experiment at the scale of a power plant is necessarily a large facility and integrates multiple advanced technologies. At the present time, no country has the combination of scientific and engineering expertise, industrial capacity, and long-term national commitment to undertake this critical task alone.

While previous studies concluded that fusion energy research substantially benefits from international cooperation, they also described a potential for failure if international partners were unable to meet their commitments. The 2009 NRC report *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program* recommended that steps should be taken to "seek greater U.S. funding stability for the international ITER project to ensure that the United States remains able to influence the developing ITER research program, to capitalize on research at ITER to help achieve U.S. fusion energy goals, to participate in obtaining important scientific results on burning plasmas from ITER, and to be an effective participant in and beneficiary of future international scientific collaborations."[8]

The committee has reviewed the recommendations from these past studies in the context of the existing ITER partnership, the assessments of U.S. burning plasma research listed above, and the benefits international partnership brings to large multi-year endeavors at the frontier. Based on this review, the committee concludes that the United States benefits from partnership in ITER as the primary experimental burning plasma component within its own long-term strategic plan for fusion energy. On the other hand, a decision by the United States to withdraw from the ITER project would require a new approach to study a burning plasma. Because there is currently no

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[3] NRC, *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, Washington, D.C., 1984.

[4] NRC, *Pacing the U.S. Magnetic Fusion Program*, National Academy Press, Washington, D.C., 1989.

[5] President's Committee of Advisors on Science and Technology, *The U.S. Program of Fusion Research and Development*, Washington, D.C., July 11, 1995.

[6] U.S. Department of Energy, *Realizing the Promise of Fusion Energy: Final Report of the Task Force on Fusion Energy*, Secretary of Energy Advisory Board, Washington, D.C., August 9, 1999.

[7] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[8] NRC, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, Washington, D.C., 2009, pp. 2-3.

mature burning plasma experiment as an alternative to ITER, the design, construction, and licensing of such an alternative to ITER would require significant development by the U.S. program, as well as a new approach to avoid isolation from the international fusion energy research effort.

The committee's final report will provide greater detail and analysis of the options for a long-term strategic plan for a national program of burning plasma science and technology research, including developing various supporting capabilities and participating in international activities. Strategic guidance for scenarios where the United States both is and is not a participant in ITER will be described.

Work for the final report is at an early stage. Nevertheless, based on the input received by the committee and the committee's assessments, if the United States seeks to continue its pursuit for abundant fusion power, the development of a national strategic plan for fusion energy that spans several decades is necessary. Therefore, the committee makes the following final assessment that will guide the strategies for both scenarios in the final report.

Assessment 7: If the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy.

In the development of the final report, the committee views the following elements as important to its guidance on a long-term strategic plan:

- Continued progress towards the construction and operation of a burning plasma experiment leading to the study of burning plasma,
- Research beyond what is done in a burning plasma experiment to improve and fully enable commercial fusion power,
- Innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and
- A mission for fusion energy research that engages the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

1

Background

On January 30, 2003, just 6 weeks after the release of the interim report of the National Research Council's (NRC's) Burning Plasma Assessment Committee,[1] the focus and priority of the U.S. fusion energy sciences program changed. President George W. Bush announced "that the United States will join an ambitious international research project to harness the promise of fusion energy, the same form of energy that powers the Sun."[2] The President's announcement described the International Thermonuclear Experimental Reactor (ITER) as "the largest and most technologically sophisticated fusion experiment in the world." The President also acknowledged the NRC's recommendation for U.S. participation in ITER and further explained, "This step is critical to the development of fusion as a viable energy source. Recent scientific developments have advanced knowledge of this field to the point that scientists now believe ITER can demonstrate the feasibility of this technology as part of an ongoing effort to develop a practical energy-generating device. If successful, ITER would create the first fusion device capable of producing thermal energy comparable to the output of a power plant, making commercially viable fusion power available as soon as 2050."

The importance of a burning plasma experiment as a required step in the development of practical fusion energy has been appreciated for decades.[3] "A burning plasma experiment would address for the first time the scientific and technological questions that all energy-producing fusion schemes must face."[4] As explained in the 1999 Fusion Energy Sciences Advisory Committee (FESAC) report *Burning Plasma Physics*, "Producing and understanding the dynamics of a burning plasma will be an immense physics challenge and the crucial next step in establishing the credibility of fusion as a source of energy."[5] This finding was also enunciated by previous review panels, which additionally noted the required international, scientific, and political support for the endeavor to construct and operate a burning plasma experiment.[6] The President's Committee of Advisors in Science and Technology (PCAST) report of the Fusion Review Panel[7] and the 1996 report of the Fusion Energy Advisory Council (FEAC), *Restructured Fusion Energy Sciences Program*, recommended that the United States should "pursue fusion energy science and technology as a partner in the international effort."[8] The report of the NRC Fusion Science Assessment Committee recommended that "solid support should be developed within the broad

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[1] National Research Council (NRC), *Letter Report: Burning Plasma Assessment (Phase 1)*, The National Academies Press, Washington, D.C., 2002.

[2] George W. Bush: Fact Sheet: ITER, January 30, 2003. Available online by G. Peters and J.T. Woolley, The American Presidency Project, http://www.presidency.ucsb.edu/ws/?pid=80124.

[3] See, for example, U.S. Department of Energy (DOE), *Final Report of the Fusion Policy Advisory Committee*, delivered to Energy Secretary Watkins, Washington, D.C., September 1990.

[4] National Research Council (NRC), *Letter Report: Burning Plasma Assessment (Phase 1)*, The National Academies Press, Washington, D.C., 2002, p. 3.

[5] DOE, *Burning Plasma Physics*, DOE/SC-0041, Fusion Energy Sciences Advisory Committee, Washington, D.C., September 1999.

[6] See, for example, NRC, *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, Washington, D.C., 1984.

[7] President's Committee of Advisors on Science and Technology, *The U.S. Program of Fusion Energy Research and Development*, Fusion Review Panel, Washington, D.C., July 1995.

[8] DOE, *A Restructured Fusion Energy Sciences Program*, Fusion Energy Advisory Committee, Washington, D.C., January 1996.

scientific community"[9] for U.S. participation in a burning plasma experiment, and the Secretary of Energy Advisory Board Task Force on Fusion Energy urged "solid support for it throughout the political system."[10]

These previous reports, the successful production of 11 MW fusion power in the Tokamak Fusion Test Reactor experiment[11] and 16 MW in JET,[12] and the plan for the U.S. magnetic fusion burning plasma experimental program as developed through the FESAC and Snowmass processes were reviewed by the 2004 NRC Burning Plasma Assessment Committee.[13] The committee's key recommendation was as follows: "The United States should participate in the International Thermonuclear Experimental Reactor (ITER) project. If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced U.S. fusion science program." Following this recommendation, the Department of Energy (DOE) *Twenty-Year Outlook*[14] listed ITER as the highest priority within the Office of Science.

Following decades of effort, including the International Tokamak Reactor project (1978-1987)[15] and the ITER Engineering Design Activity (1992-1998),[16] both facilitated through the International Atomic Energy Agency (IAEA), an international agreement to build and operate a burning plasma experiment was finally formalized in Paris with the signing of the *Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project* in November 2006.[17] The ITER International Fusion Energy Organization is a public international organization, with limited privileges and legal immunities, involving the United States with China, the European Union, India, Japan, the Republic of Korea, and the Russian Federation. At the signing ceremony, DOE Undersecretary for Science Raymond Orbach explained, "ITER is the first stand-alone, truly international, large-scale scientific research effort in the history of the world." After an international design review was completed in 2008,[18] ITER construction began in 2010 in Cadarache, France.[19] In 2012, by French Order, ITER became the first of a kind licensed basic nuclear fusion facility.[20]

By 2013, the estimated cost of ITER construction had grown substantially, and the schedule had slipped by more than a decade. As a consequence, the ITER Council charged an independent team, chaired by William Madia, former director of Oak Ridge National Laboratory and Stanford University vice president for the Stanford Linear Accelerator Center, to determine the causes for ITER's cost increases and schedule delays and to make management recommendations. Additionally, a bipartisan group of leaders in the U.S. Senate requested the Government Accountability Office to investigate the cost and feasibility of ITER and its effect on U.S. fusion programs.[21] These reports helped to motivate significant management improvements taken by the ITER Council,[22] which included the accelerated appointment of a new ITER director general.

In March 2015, Benard Bigot accepted the directorship of the ITER project and created an action plan to implement the recommendations from the 2013 management review. Following these management improvements, the resource-loaded plan to first plasma was approved by the ITER Council in June 2016. The ITER Council

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[9] NRC, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, The National Academies Press, Washington, D.C., 2001.

[10] DOE, *Realizing the Promise of Fusion Energy*, Final Report of the Secretary of Energy Advisory Board, Task Force on Fusion Energy, Washington, D.C., August 1999.

[11] Hawryluk et al., Results from deuterium-tritium tokamak confinement experiments, *Rev. Mod. Phys*. 70:537, 1998.

[12] Keilhacker et al., High fusion performance from deuterium-tritium plasmas in JET, *Nuc Fusion* 39:209, 1999.

[13] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[14] DOE, *Facilities for the Future—A Twenty Year Outlook*, Office of Science, Washington, D.C., November 2003.

[15] See INTOR TEAM, *International Tokamak Reactor: Phase 2A*, Part III, IAEA, Vienna, 1988.

[16] R. Aymar, Present status and future prospect of the ITER project, *J Nucl Mater* 258:56, 1998.

[17] See https://www.iaea.org/sites/default/files/publications/documents/infcircs/2007/infcirc702.pdf.

[18] R. Hawryluk et al., Principal physics developments evaluated in the ITER design review, *Nuclear Fusion* 49:065012, 2009.

[19] M. Banks, Construction begins, but ITER's costs spiral, *Phys. World* 23(7), 2010.

[20] Implementation at ITER of the French Order of 7 February 2012, concerning basic nuclear installations within the European Domestic Agency, P. Wouters et al., *Nucl. Fusion* 57:100401m, 2017.

[21] U.S. Government Accountability Office, *Fusion Energy: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor*, Report to Congress, GAO-14-499, Washington, D.C., June 2014.

[22] DOE, *U.S. Participation in the ITER Project*, Report to Congress, Washington, D.C., May 2016.

Working Group on the Independent Review of the Updated Long-Term Schedule and Human Resources completed its review in April 2016, and DOE approved the project execution plan for U.S. contributions to ITER in January 2017.[23]

Today, ITER construction and fabrication occurs throughout the 100-acre ITER site; more than 1,200 workers are on site; all major buildings are under construction, including cryogenic, tritium, and diagnostic buildings; and four of six levels of the concrete bioshield for the tokamak have been completed. Important milestones have been achieved,[24] including completion of the first 2 of 18 110-ton toroidal field coils by a consortium of European manufacturers in May 2016 and by the Japanese industry in February 2017, followed by the completion of the first of two 800-ton vacuum vessel sector sub-assembly tools by Korean manufactures in May 2017. Within the United States, components for the steady state electrical network were delivered in October 2017, and General Atomics, Inc. (San Diego, California) successfully completed heat treatment of the first of eight central solenoid coils that, when completed, will be more than 50 feet tall and will be the most powerful pulsed superconducting magnet in the world. It is noteworthy that after nearly 2 years since the creation of the updated long-term schedule, the ITER Council reported the project has so far remained on schedule for first plasma in 2025,[25] and all 25 milestones due by the end of second-quarter 2017 have been achieved.[26]

Achievement of government consensus on rejoining ITER, along with broad support within the U.S. scientific community, was a major accomplishment over the past decade. With this achievement came a necessary change in focus and priority of the U.S. fusion energy sciences program. As determined by the 2004 NRC Burning Plasma Assessment Committee, “once the [ITER] decision is made, fulfilling the international commitment to help construct the ITER facility and participate in the ITER program will necessarily become the highest priority in the program.”[27] The NRC Burning Plasma Assessment Committee further recommended, “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.” Four years later, the NRC Committee to Review the DOE Plan for U.S. Fusion Community Participation in the ITER Program[28] recommended that steps should be taken to “seek greater funding stability for the international ITER project to ensure that the United States remains able to influence the developing ITER research program, to capitalize on research at ITER to help achieve U.S. fusion energy goals, to participate in obtaining important scientific results on burning plasmas from ITER, and to be an effective participant in and beneficiary of future international scientific collaborations.”

Following these NRC recommendations, ITER became a primary research focus of the U.S. program. For fiscal year (FY) 2014, the U.S. ITER Project received about 40 percent of the U.S. fusion program budget.[29] The DOE Office of Fusion Energy Sciences (FES) annual budget requests to Congress FY2015 through FY2017 stated that the results from U.S. fusion research “support U.S. goals for future scientific exploration on ITER.”

This focus resulted in significant burning plasma research advancements and improved confidence in ITER burning plasma performance. However, other fusion energy science and technology efforts that did not directly support ITER were reduced or eliminated in order to emphasize research in support of ITER. DOE’s FY2005 budget request to Congress called for reduced U.S. fusion technology efforts. In a letter to FESAC, Undersecretary Orbach wrote that “funding for the energy relevant technology research and development will wait for the results of ITER” and further explained, “Until we are confident that we understand the science of fusion, we would be taking an unacceptable risk to commit the sums required to develop the technology needed to apply that science.”[30] The National Compact Stellarator Experiment under construction at the Princeton Plasma Physics Laboratory was

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[23] DOE, *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, Office of Science, Fusion Energy Sciences, Washington, D.C., January 2017.

[24] Ned R. Sauthoff, “Perspectives from the US ITER Project,” presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research on August 29, 2017.

[25] International Thermonuclear Experimental Reactor (ITER) Council, *Report of the 20th Meeting of the ITER Council*, June 22, 2017, https://www.iter.org/news/pressreleases.

[26] Ned R. Sauthoff, “Perspectives from the US ITER Project,” presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research, August 29, 2017.

[27] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[28] NRC, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, Washington, D.C., 2009.

[29] DOE FY2015 budget request.

[30] Fusion Power Associated, *DOE Plans Termination of All Fusion Technology Efforts*, FPN04-17, March 10, 2004, http://aries.pppl.gov/FPA/ARC04/fpn04-17.shtml.

canceled in 2008 in part owing to the higher priority given to participation in ITER, which is based on the tokamak and not the stellarator concept. Exploratory fusion experiments at the intermediate-scale were eliminated in the FY2011 budget in favor of research that "can contribute to our understanding and optimizing the tokamak configuration and configurations closely related to it."[31] The DOE's FY2013 request for fusion energy science proposed an "overall reduction in domestic research" while making "a modest increase in funding for scientific collaborations on major international facilities." In inflation adjusted amounts, funding for domestic fusion research has declined since 2002 while U.S. participation in international research has increased.[32]

The current priorities of the U.S. DOE/FES program aim to establish a knowledge base that supports U.S. goals for future scientific exploration on ITER. Using input from three community workshops, the 2015 *Ten-Year Perspective* for the DOE/FES program emphasizes three research areas: (1) massively parallel computing with the goal of validated whole-fusion-device modeling, (2) materials research as it relates to plasma and fusion science, and (3) research in the prediction and control of transient events that can be deleterious to toroidal fusion plasma confinement.[33] Research in these areas address two frontiers in fusion and plasma science: "the physics of self-heated burning plasma state" using ITER as the vehicle for gaining access to this state, and the "great scientific challenge for fusion is to develop materials that can tolerate the extreme conditions created by burning plasma in a fusion reactor." The U.S. DOE/FES program budget is constructed from three elements[34]: (1) Burning Plasma Science: Foundations; (2) Burning Plasma Science: Long Pulse; and (3) Burning Plasma Science: High Power. Each of these three program elements significantly contribute to developing the predictive understanding needed for ITER operations and providing solutions to high-priority ITER research needs. A fourth element, Discovery Plasma Science, supports research that advances fundamental plasma understanding and explores ways to control and manipulate plasmas for non-fusion applications.

The 2015 *Ten-Year Perspective* states (p. ii) the overall mission of the U.S. DOE/FES program is "to expand the fundamental understanding of matter at very high temperatures and densities and build the scientific foundation needed to develop a fusion energy source."[35] By comparison, EUROfusion (the consortium agreement of research organizations and universities from 26 European Union countries plus Switzerland, Ukraine, and formerly the European Fusion Development Agreement) is guided by a roadmap to supply fusion electricity to the grid by the 2050s.[36] Similar national roadmaps leading to the demonstration of fusion power guide research in China[37] and Japan.[38]

Presently, the U.S. fusion research program is focused on future scientific exploration of the burning plasma state in ITER. If the United States were to withdraw from participation in the ITER project, no alternate plan exists for accessing critical next-step burning plasma research at a scale leading to commercial fusion energy. Furthermore, the May 2016 Secretary of Energy's Report to Congress states, "ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power."[39]

The baseline cost and schedule for U.S. contributions to the ITER's first plasma subproject are now formalized.[40] Through FY2016, the United States has contributed one-third of its obligated construction costs to first plasma, or $1,138 million. Including contingency, the remaining U.S. hardware and cash contributions to first

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[31] T. Feder, U.S. narrows fusion research focus, joins German stellarator, *Phys. Today*, September 2011, p. 30.

[32] Based on appropriated budgets reported in the DOE Fusion Energy Sciences annual budget requests to Congress for FY2003 and FY2017.

[33] DOE, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, Washington, D.C., December 2015.

[34] See DOE Fusion Energy Sciences annual budget requests to Congress for FY2015 through FY2017.

[35] DOE, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, Washington, D.C., December 2015.

[36] European Fusion Development Agreement (EFDA), *Fusion Electricity: A Roadmap to the Realization of Fusion Energy*, November 2012, https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf.

[37] Wu et al., Identification of safety gaps for fusion demonstration reactors, *Nature Energy* 1:16154, 2016.

[38] Yamada et al., Japanese endeavors to establish technological bases for DEMO, *Fusion Eng and Design* 109:1318-1325, 2016.

[39] DOE, *U.S. Participation in the ITER Project*, Report to Congress, Washington, D.C., May 2016.

[40] DOE, *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, Office of Science, Fusion Energy Sciences, Washington, D.C., January 2017.

plasma construction is an additional $2,210 million over the next decade. Post-first plasma construction leading to experiments with a burning plasma will require at least $1,500 million additional summed over the decade after first plasma. Continued U.S. participation in the ITER project requires an additional $100 million to $125 million annually for more than two decades, and, "future budget planning for continued support for ITER needs to be considered within the context of the total budget for SC [Office of Science], and not merely within the FES program."[41]

These newly baselined cost and schedule estimates for ITER, which is a major component of the U.S. fusion energy program, and the need for scientific and technological advances in addition to those that will be made with ITER, define the context for the committee's consideration of elements within a long-term U.S. fusion energy research strategy.

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[41] DOE, *U.S. Participation in the ITER Project*, Report to Congress, Washington, D.C., May 2016.

2

The Committee’s Information-Gathering Process

The assessments in this report are based on the following:[1]

- Review of many past studies on magnetic fusion energy and research needs that were written to guide fusion energy research strategy for the United States and for Europe, China, Japan, and the Republic of Korea;
- The December 2015 report to Congress from the Acting Director, Department of Energy Office of Science, titled *A Ten-Year Perspective* and describing the present U.S. activities in fusion plasma and materials science;
- The May 2016 report to Congress from the Secretary of Energy on U.S. Participation in the International Thermonuclear Experimental Reactor (ITER) Project;
- The Project Execution Plan for the U.S. Contributions to ITER Subproject-1 (U.S. ITER SP-1) Project Number 14-SC-60, released in January 2017;
- Narratives from the annual budget request from the Department of Energy, Office of Science Fusion Energy Sciences Program, and the Reports from the congressional Energy and Water Development Appropriations Subcommittees;
- Briefings, reports of ongoing research, and presentations of strategies provided as input to the committee as part of the public record;
- Written documents and oral presentations made during the first two meetings of the committee;
- Input from the first of two community workshops on strategic directions for U.S. magnetic fusion research held at the University of Wisconsin, Madison, from July 24-28, 2017;
- Relevant review articles published in the scientific literature—for example, describing (1) scientific and technical achievements since the 2004 report of the National Research Council (NRC) Burning Plasma Assessment Committee,[2] (2) the magnetic fusion energy development path,[3] (3) the scientific opportunity afforded by study of a burning plasma experiment,[4,5] and (4) the plan of Director General Bernard Bigot to correct organizational problems and sustain ITER construction performance;[6] and
- Expertise of the committee’s membership including magnetic and inertial fusion energy, fusion materials science, fusion engineering science, plasma science, and nuclear science and engineering.

A short description of the science and history of magnetic fusion energy research is given in Appendix A. The statement of task for the committee is in Appendix B. The agendas for the committee’s first two meetings are provided in Appendix C. A bibliography of prior reports and studies consulted by the committee is provided in Appendix D.

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[1] See Appendix D for the source material used for the committee’s information-gathering process.

[2] National Research Council, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[3] C.L. Smith and S. Cowley, The path to fusion power, *Philosophical Transactions of the Royal Society A: Mathematical*, *Physical and Engineering Sciences* 368:1091, 2010.

[4] J. Ongena, R. Koch, R. Wolf, and H. Zohm, Magnetic-confinement fusion, *Nature Phys* 34:398, 2016.

[5] A. Fasoli, S. Brunner, W.A. Cooper, J.P. Graves, P. Ricci, O. Sauter, and L. Villard, Computational challenges in magnetic-confinement fusion physics, *Nature Phys* 12:411, 2016.

[6] B. Bigot, Nuclear physics: Pull together for fusion, *Nature* 522:149, 2015.

3

Importance of Burning Plasma Research

The committee reaffirms the importance of burning plasma research to the development of fusion energy, as well as to plasma science and other science and engineering disciplines.

IMPORTANCE TO THE DEVELOPMENT OF FUSION ENERGY: CONTROLLING A BURNING PLASMA

As explained in the 2004 report of the Burning Plasma Assessment Committee of the National Research Council (NRC), "A burning plasma experiment would address for the first time all of the scientific and technological questions that all magnetic fusion schemes must face. Such an experiment is the crucial element missing from the world fusion energy science program and a required step in the development of practical fusion energy."[1] The integrated challenges of understanding the dynamics of a burning plasma and of applying the high-technology know-how to heat, sustain, and control a burning plasma within the International Thermonuclear Experimental Reactor (ITER) has helped to focus research, improve understanding and predictive capability, and address key concerns such as transients, increasing confidence in the success of ITER as a burning plasma experiment.

Experiments within the United States have led to significant progress in all important areas identified in the 2004 NRC report. These are as described below.

A burning plasma experiment will represent the first time that a confined fusion plasma is dominated by fusion-born alpha particles. Energetic alpha particles from fusion reactions are predicted to drive plasma instabilities, which could, if not mitigated, substantially reduce fusion power produced and potentially damage the reactor inner wall. Consequently, it is vital to understand how energetic alpha particles affect plasma dynamics. In 2004, such instabilities had been observed and their behavior in different circumstances had begun to be characterized. Now, the onset of energetic particle instabilities is understood, and promising techniques to control these instabilities are being investigated. Predictive models are being developed and compared to advanced fluctuation and fast ion diagnostic measurements. Despite considerable progress understanding fusion-born alpha physics, detailed identification of nonlinear mechanisms is just beginning. Beyond validation of theoretical models, important research areas also include methods to control energetic particles instability for helpful purposes such as favorably modifying the current profile or to govern the nonlinear dynamics to control fusion burn.[2,3]

A burning plasma experiment advances understanding of plasma transport properties from the core to the boundary. A burning plasma can be divided into an inner high-temperature core where fusion reactions occur, a surrounding insulating layer called the pedestal, and a boundary layer where escaping plasma flows to a protective divertor. Since 2004, major advances in theory and computation have resulted in detailed understanding of turbulent transport in the plasma core and the key physics processes regulating the pedestal structure in high-confinement mode (called "H-mode") plasmas. Recently developed computational techniques to couple core and edge physics

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[1] National Research Council (NRC), *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[2] Chen and Zonca, Physics of Alfvén waves and energetic particles in burning plasmas, *Rev Mod Phys* 88:015008, 2016.

[3] Gorelenkov, Pinches, Toi, Energetic particle physics in fusion research in preparation for burning plasma experiments, *Nuc Fusion* 54:125001, 2014.

have been extensively tested against experiments, resulting in significantly improved capability to predict fusion performance.[4] For illustration, these computational tools predicted new high-performance regimes that were subsequently observed in experiments of the U.S. fusion research program.[5] Although there has been considerable progress made in predicting plasma transport, the validity of these predictions must be tested in future burning plasma experiments. Some of the highest performance discharges studied in DIII-D experiments decrease performance when produced with lower injected torque, as expected in ITER.[6] Furthermore, additional research is needed to understand confinement scaling towards desirable fusion reactor conditions characterized by high plasma beta, steady state, and compatible divertors.

A burning plasma experiment enables critical tests to control plasma transients. Due to the large stored energy of a burning plasma, transient events, which cause rapid energy loss from the plasma, present a significant risk to material lifetimes. Transients include disruptions (i.e., when plasma current and confinement are lost) and edge localized modes (ELMs) (i.e., the outer edge plasma is lost). Since 2004, the United States has made substantial progress understanding transients and demonstrating methods either to avoid or to mitigate transients. Notably, ELMs can be avoided via U.S.-discovered operation regimes, such as the Quiescent H-Mode (Q-H-mode),[7] Enhanced Pedestal H-mode (EP-H-mode), or I-mode regime,[8] or actively controlled by applying resonant magnetic perturbations[9] (a technique pioneered in the United States), pellet injection, and position control.[10] The United States has also led the world in the development of techniques for understanding, as well as predicting, avoiding and/or controlling disruptions of the plasma current—the latter by massive gas injection,[11] shattered pellets, and shell pellets.[12] These techniques are critical for ITER and other burning plasma devices based on the tokamak; however, additional research is needed to understand the science of both ELM suppression and disruption avoidance at the higher temperatures, magnetic energies, and potentially longer current quench times expected in a burning plasma experiment.[13]

A burning plasma experiment advances divertor science necessary for a fusion power source. Unless controlled, the power escaping from a burning plasma will lead to inner wall damage. Control of escaping heat and particles is made by carefully shaping the magnetic field so that plasma flows along the plasma boundary[14] and into a divertor, where the plasma heat and particle flux can be nearly extinguished by interaction with recycling neutrals.[15] Additionally, because carbon-based first-wall materials must have low tritium retention,[16] important plasma-material processes such as erosion, tritium co-deposition, dust generation, and neutron-irradiation damage

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[4] Kinsey et al., ITER predictions using the GYRO verified and experimentally validated trapped gyro-Landau fluid transport model, *Nuc Fusion* 51:083001, 2011.

[5] Solomon et al., Exploration of the Super H-mode regime on DIII-D and potential advantages for burning plasma devices, *Phys Plasmas* 23:056105, 2016.

[6] Buttery et al., DIII-D research to address key challenges for ITER and fusion energy, *Nuc Fusion* 55:104017, 2015.

[7] Snyder et al., Stability and dynamics of the edge pedestal in the low collisionality regime: Physics mechanisms for steady-state ELM-free operation, *Nuc Fusion* 47:961-968, 2007.

[8] Whyte et al., I-mode: an H-mode energy confinement regime with L-mode particle transport in Alcator C-Mod, *Nuc Fusion* 50:105005, 2010.

[9] Evans et al., RMP ELM suppression in DIII-D plasmas with ITER similar shapes and collisionalities, *Nuc Fusion* 48:024002, 2008.

[10] Loarte et al., Progress on the application of ELM control schemes to ITER scenarios from the non-active phase to DT operation, *Nuc Fusion* 54:033007, 2014.

[11] Hollmann et al., Measurements of injected impurity assimilation during massive gas injection experiments in DIII-D, *Nuc Fusion* 48:115007, 2008.

[12] Commaux et al., Demonstration of rapid shutdown using large shattered deuterium pellet injection in DIII-D, *Nuc Fusion* 50:112001, 2010.

[13] Lehnen et al., Impact and mitigation of disruptions with the ITER-like wall in JET, *Nuc Fusion* 53:093007, 2013.

[14] Goldston, Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks, *Nuc Fusion* 52:013009, 2012.

[15] Krasheninnikov et al., Edge and divertor plasma: Detachment, stability, and plasma-wall interactions, *Nuc Fusion* 57:102010, 2017.

[16] Skinner et al., Recent advances on hydrogen retention in ITER's plasma-facing materials: Beryllium, carbon, and tungsten, *Fusion Sci and Tech* 54:891, 2008.

require evaluation in a burning plasma experiment.[17] The U.S. research program has significantly advanced understanding of burning plasma boundary physics, including improved understanding of the narrow "scrape-off layer" connecting the confined plasma to the divertor. The U.S. research program has also developed and successfully tested several innovative divertor concepts.[18,19] Further developments for a divertor with long lifetime remains a major fusion research challenge.

A burning plasma experiment tests integrated scenarios that simultaneously test the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components needed for a fusion energy source. Since 2004, plasma operation and control scenarios have been developed and tested in preparation for ITER experiments.[20] Additionally, high-fidelity integrated models,[21] which take full benefit from advances in high-performance computing, are now routinely used to interpret experimental measurements and make progress in predicting the results of burning plasma experiments.[22] The U.S. research program has led the world in the development of quiescent plasma scenarios not subject to damaging transient events[23] and the so-called "advanced inductive scenario,"[24] which can achieve the same plasma performance at reduced plasma current and so minimize the risk of disruption damage. A burning plasma experiment can also test other advanced scenarios, like the so-called "super H-mode," which represents an attractive area of innovation aimed to reduce the size of a fusion device with improved confinement. Further research using a burning plasma experiment is needed to develop understanding for integrated scenarios that address the challenges of steady-state operation, robust stability at low plasma rotation and high plasma pressure,[25] and compatible divertor concept.[26,27]

The importance of U.S. advances in these key areas has been broadly recognized. For example, the European Physical Society named plasma physicists working in the United States during 6 of the 18 years since awarding the prestigious Hans Alfvén Prize.[28] Also, 8 of the 11 Nuclear Fusion Awards were presented to U.S. scientists working on scenarios, transport, stability, transient control, boundary, and pedestal physics.[29]

IMPORTANCE TO THE DEVELOPMENT OF FUSION ENERGY: FUSION TECHNOLOGY

While burning plasma science has progressed since the 2004 NAS burning plasma assessment, significant advancements in fusion technology are needed for a burning plasma reactor. Below are brief descriptions of a

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[17] Roth et al. Recent analysis of key plasma wall interactions issues for ITER, *J Nuc Materials* 390-91:1-9, 2009.

[18] Kugel et al., Evaporated lithium surface coatings in NSTX, *J. Nuc Materials* 390-91:1000-1004, 2009.

[19] Umansky et al., Attainment of a stable, fully detached plasma state in innovative divertor configurations, *Phys Plasmas* 24:056112, 2017.

[20] Solomon et al., DIII-D research advancing the scientific basis for burning plasmas and fusion energy, *Nuc Fusion* 57:102018, 2017.

[21] McClenaghan et al., Transport modeling of the DIII-D high beta(p) scenario and extrapolations to ITER steady-state operation, *Nuc Fusion* 57:116019, 2017.

[22] Sips et al., Progress in preparing scenarios for operation of the International Thermonuclear Experimental Reactor, *Phys Plasmas* 22:021804, 2015.

[23] Hubbard et al., Physics and performance of the I-mode regime over an expanded operating space on Alcator C-Mod, *Nuc Fusion* 57:126039, 2017.

[24] Luce et al., Development of advanced inductive scenarios for ITER, *Nuc Fusion* 54:013015, 2014.

[25] Evans et al., ELM suppression in helium plasmas with 3D magnetic fields, *Nuc Fusion* 57:086016, 2017.

[26] Wenninger et al., Advances in the physics basis for the European DEMO design, *Nuc Fusion* 55:063003, 2015.

[27] Ongena et al., Magnetic-confinement fusion, *Nat Phys* 34:398, 2016.

[28] Alfvén Prize winners: Marshall N. Rosenbluth (2002), Liu Chen (2008), Allen Boozer (2010), Patrick Diamond and Akira Hasegawa (2011), Miklos Porkolab (2013), and Nathaniel Fisch (2015). (See http://plasma.ciemat.es/eps/awards/alfven-prize/).

[29] The Nuclear Fusion Award has been given annually since 2006. U.S. award recipients are Tim Luce (2006 General Atomics), Todd Evans (2008 General Atomics), Steve Sabbagh (2009 Columbia University), John Rice (2010 MIT), Pat Diamond (2012 University of California, San Diego), Dennis Whyte (2013 MIT), Phil Snyder (2014 General Atomics), and Rob Goldston (2015 Princeton University). See http://www-pub.iaea.org/books/iaeabooks/Nuclear_Fusion/NF/NFAward.

selected number of important science and technology contributions from fusion technology research and their impacts on fusion energy development.

Fusion blanket design, tritium breeding, fuel processing. A fusion 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 needed for the development of fusion energy. Fusion reactors must operate with more tritium produced and recovered than is burned. The vast majority of the fuel injected in a fusion chamber will not be burned in a single pass. Unburned deuterium-tritium fuel will be continuously transported to the plasma edge, where it must be exhausted, stripped of impurities, and then reinjected into the plasma. A burning plasma experiment provides the opportunity to test and evaluate the performance of prototypical blanket modules and demonstrate technologies for tritium extraction from blankets and for fuel processing systems that can be operated efficiently at large scale.[30,31,32]

Fusion safety, remote handling, and waste management. A burning plasma experiment offers the opportunity to begin development of the technologies needed for a fusion reactor, including important safety-related technologies. Many components and systems needed for fusion's safety objectives are unique, such as source diagnostics and cleaning technologies, state-of-the-art safety analyses tools, technologies for the remote handling of large activated components, technologies for the control of routine tritium releases, and innovative approaches for the control of tritiated and mixed waste streams.[33] A burning plasma experiment will be an integrated demonstration of the safety, reliability, and effectiveness of these technologies.[34]

Fusion materials science. The behavior and integrity of materials in a fusion system are of great importance to the long-term viability of fusion energy.[35] The high flux of energetic neutrons to the vessel and structural materials poses a serious materials problem that will require substantial testing, some of which may be done on a burning plasma experiment.[36] The high energy neutrons from the D-T fusion reaction generate between 50- to 100-times-higher He/dpa in materials such as ferritic steels than does fission reactor irradiation. Burning plasma experiments will also aid in the development of high-heat-flux components and will serve as testbeds in which to evaluate the performance of the components in a reactor-like fusion environment. The heat loads on components in a burning plasma experiment will be comparable to those expected in a reactor and will require the application of state-of-the-art high-heat-flux technology using materials that satisfy requirements of tritium retention, safety, structural integrity, lifetime, and plasma compatibility.[37,38,39]

Plasma heating and current drive systems for fusion. Plasma heating by electromagnetic waves and neutral particle beams are needed to heat the plasma to a burning state,[40] sustain plasma current,[41] modify temperature and current profiles, and control plasma instabilities.[42] Ion cyclotron heating is one primary method for heating the bulk plasma, while lower hybrid current drive is perhaps the most efficient radio-frequency method to drive a steady-state

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[30] Sawan and Abdou, Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle, *Fusion Eng and Design* 81:1131-1144, 2006.

[31] Giancarli et al., Overview of the ITER TBM Program, *Fusion Eng and Design* 87:395, 2012.

[32] National Research Council, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[33] Girard et al., TER, safety and licensing, *Fusion Eng Des* 82:506, 2007.

[34] Bornschein et al., Tritium management and safety issues in ITER and DEMO breeding blankets, *Fusion Eng Des* 88:466, 2013.

[35] Zinkle and Snead, Designing radiation resistance in materials for fusion energy, *Annu. Rev. Mater. Res.* 44:241, 2014.

[36] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[37] Raffray et al., High heat flux components-Readiness to proceed from near term fusion systems to power plants, *Fusion Eng and Design* 85:93-108, 2010.

[38] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[39] Ibid.

[40] Omori et al., Overview of the ITER EC H&CD system and its capabilities, *Fusion Eng and Design* 86:951-954, 2011.

[41] Cesario et al., Current drive at plasma densities required for thermonuclear reactors, *Nature Comm* 1:55, 2010.

[42] Sauter et al., On the requirements to control neoclassical tearing modes in burning plasmas, *Plasma Phys Control Fusion* 52:025002, 2010.

toroidal current. Sources are available for both applications.[43] Electron cyclotron resonance heating can also be used for bulk electron heating, profile control, pre-ionization/startup, and current drive in burning plasmas, but here further source development is still needed. Fusion reactor research continues to push the frontiers of high power mm-wave and radio-frequency technology.[44]

High-field magnet technology for fusion. Strong magnetic fields are critical to the success of magnetic fusion as a source of energy. Achieving higher magnetic field strength extends the allowable plasma properties to higher plasma density, higher plasma current, and higher plasma pressure while retaining the same dimensionless scaling parameters found at lower magnetic field strength. This extended range of plasma parameters from high-field magnets allows more compact tokamak devices that may provide a lower cost path to future fusion reactors. ITER's superconducting magnet system will be the largest ever made and is designed to operate with the highest practical magnetic field strength for large toroidal field coils made of Niobium-Tin superconductors and consistent with the strength of steel.[45] New developments of rare-earth barium-copper-oxide high-temperature superconductors may lead to larger magnetic field strength and potentially improve the prospects for magnetic fusion energy.[46,47] However, the costs and performance of these advanced superconductors will not be fully understood without experience at the industrial scale,[48] and new integrated scenarios for high-field fusion must be developed and tested.[49]

Integrated systems engineering for fusion. Systems engineering combines plasma physics and engineering constraints into a self-consistent integrated design for large-scale fusion facilities. Systems engineering studies have been carried out for various types of tokamak reactors, including the advanced tokamak,[50] high-field tokamak,[51] spherical tokamak, and stellarator.[52] The recent Advanced Reactor Innovation and Evaluation Study—Advanced and Conservative Tokamak tokamak studies[53] are a good example covering the four possible options of optimistic versus conservative physics and/or engineering. The value of these studies is to learn the strengths and weaknesses of any given concept and to point out which physics or engineering quantities have high leverage in improving reactor performance and economics.

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[43] Hill et al., DIII-D research towards resolving key issues for ITER and steady-state tokamaks, *Nuc Fusion* 53:104001, 2013.

[44] Thumm, M., Recent advances in the worldwide fusion gyrotron development, *IEEE Trans Plasma Sci* 42:590-599, 2014.

[45] Mitchell and Devred, The ITER magnet system: Configuration and construction status, *Fusion Eng. Des.* 2017, http://dx.doi.org/10.1016/j.fusengdes.2017.02.085, in press.

[46] Fietz et al., Prospects of high temperature superconductors for fusion magnets and power applications, *Fusion Eng Des* 88:440, 2013.

[47] Takayasu et al., Investigation of HTS twisted stacked-tape cable (TSTC) conductor for high-field, high-current fusion magnets, *IEEE Trans Applied Superconductivity* 27:1, 2017.

[48] Green and Strauss, Things to think about when estimating the cost of magnets made with conductors other than Nb-Ti, *IEEE Trans on Applied Superconductivity* 27:1, 2017.

[49] Whyte et al., Smaller and sooner: Exploiting high magnetic fields from new superconductors for a more attractive fusion energy development path, *J Fusion Energy* 35:41, 2016.

[50] Chan et al., Physics basis of a fusion development facility utilizing the Tokamak approach, *Fusion Sci and Technology* 57:66-93, 2010.

[51] Whyte et al., Smaller and sooner: Exploiting high magnetic fields from new superconductors for a more attractive fusion energy development path, *J Fusion Energy* 35:41, 2016.

[52] Menard et al., Prospects for pilot plants based on the tokamak, spherical tokamak and stellarator, *Nuc Fusion* 51:103014, 2011.

[53] C.E. Kessel et al., The ARIES Advanced and Conservative Tokamak Power Plant Study, *Fusion Science and Technology* 67:1-21, 2015, doi: 10.13182/FST14-794.

IMPORTANCE TO PLASMA SCIENCE AND OTHER SCIENCE

The process of creating a fusion-based energy supply on Earth has led to technological and scientific achievements of far-reaching impact that touch every aspect of our lives. Those largely unanticipated advances span a wide variety of fields in science and technology and were the focus of a 2015 Fusion Energy Sciences Advisory Committee report, *Applications of Fusion Energy Research: Scientific and Technological Advances Beyond Fusion.*[54] There are many synergies between research in plasma physics and other fields, including high-energy physics and condensed matter physics, dating back many decades. For instance, the formulation of a mathematical theory of solitons, solitary waves which are seen in everything from plasmas to water waves to Bose-Einstein Condensates, has led to an equally broad range of applications in the fields of optics, fluid mechanics, and biophysics. Another example, the development of a precise criterion for transition to chaos in Hamiltonian systems has offered insights into a range of phenomena including planetary orbits, two-person games, and changes in the weather.[55] Burning plasma physics also contributes to understanding important plasma processes like magnetic reconnection,[56] kinetic turbulent processes in magnetized plasma,[57] nonlinear wave-particle interactions and resonances,[58] and multi-scale phenomena that are also common to space and astrophysical plasma.[59] Materials research in support of burning plasma science contributes to better understanding of irradiated materials.[60,61] Additionally, fusion facilities can be used to advance fundamental and non-fusion plasma physics.[62]

In assessing the importance of burning plasma research to other fields of science and technology, the committee notes that the Department of Energy Office of Fusion Energy Sciences distinguishes “burning plasma research” from the “discovery plasma science” component of the its program. It is not, in the committee’s opinion, possible to justify the construction of a burning plasma experiment based on its ability to answer questions of relevance to other fields (for example, astrophysics), yet the broad program that must necessarily be in place to exploit the results from such an experiment will have a profound effect on other fields. For example, the tremendous advances made in computational plasma physics addressing burning plasma issues have had, and will continue to have, important impact on space and astrophysical questions where the intrinsic multi-scale, multi-physics nonlinear interactions can only be addressed by large-scale computations.[63] Generally speaking, burning plasma research acts as an important driver for the development of novel concepts and methods at the interface between plasma physics, materials science,[64] applied mathematics,[65] and computer science,[66] with wide visibility and impact.[67]

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[54] U.S. Department of Energy (DOE), *Applications of Fusion Energy Sciences Research: Scientific Discoveries and New Technologies Beyond Fusion*, Fusion Energy Sciences Advisory Committee, Office of Science, September 2015, https://science.energy.gov/~/media/fes/fesac/pdf/2015/2101507/FINAL_FES_NonFusionAppReport_090215.pdf.

[55] Ibid.

[56] Yamada, Kulsrud, and Ji, Magnetic reconnection, *Rev. Mod. Phys*. 82:603, 2010.

[57] Howes, Kinetic Turbulence, pp. 123-152 in *Magnetic Fields in Diffuse Media* (Lazarian, de Gouveia Dal Pino, and Melioli, eds.), Springer Berlin Heidelberg, Berlin, Heidelberg, 2015.

[58] Breizman, Nonlinear consequences of energetic particle instabilities, *Fusion Sci and Tech*. 59:549-560, 2011.

[59] Burch et al., Magnetospheric multiscale overview and science objectives, *Space Sci Rev* 199:5-21, 2016.

[60] Zinkle and Snead, Designing radiation resistance in materials for fusion energy, *Annu. Rev. Mater. Res.* 44:241, 2014.

[61] Bai et al., Efficient annealing of radiation damage near grain boundaries via interstitial emission, *Science* 327:1631, 2010.

[62] See, for example, the DIII-D Frontier Science Campaign, https://fusion.gat.com/global/diii-d/frontier.

[63] Schekochihin et al., Astrophysical gyrokinetics: Kinetic and fluid turbulent cascades in magnetized weakly collisional plasmas, *ApJS* 182:310, 2009.

[64] Odette, Alinger, and Wirth, Recent developments in irradiation-resistant steels, *Ann Rev Mat Res*. 38:471-503, 2008.

[65] Dongarra, Hittinger (Co-Chairs) et al., *Applied Mathematics Research for Exascale Computing,* Report of DOE Working Group on Exascale Mathematics, 2014, http://science.energy.gov/~/media/ascr/pdf/research/am/docs/EMWGreport.pdf.

[66] Batchelor et al., Simulation of fusion plasmas: Current status and future direction, *Plasma Sci and Techn* 9:312, 2007.

[67] DOE, *Scientific Grand Challenges: Fusion Energy Science and the Role of Computing at the Extreme Scale*, Report from the DOE Workshop, held March 18-20, 2009, Washington, D.C.

The substantial impacts of burning plasma research on science, technology, and engineering were identified in the 2004 Burning Plasma Assessment Committee report,[68] and these have continued in several areas: (1) basic plasma science, (2) low-temperature plasmas, (3) space and astrophysical plasmas, (4) high energy density laboratory plasmas and inertial fusion energy, and (5) particle accelerator technology. Another area of technology which has benefitted from fusion research is high frequency high power millimeter wave sources (e.g., gyrotrons[69]), which have medical and industrial processing applications.[70]

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[68] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[69] Rzesnicki et al., 2.2-MW record power of the 170-GHz European Preprototype Coaxial-Cavity Gyrotron for ITER, *IEEE Trans Plasma Sci* 38, pp. 1141-1149, 2010.

[70] Sabchevski et al., A dual-beam irradiation facility for a novel hybrid cancer therapy, *J. Infrared Millimeter and THz Waves* 34:71, 2013.

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Status of U.S. Research that Supports Burning Plasma Science

Since the National Research Council (NRC) report in 2004,[1] the United States has undertaken an enormous effort in experimental, theoretical, and computational research in support of burning plasma science. The U.S. research program motivated world-leading contributions to science and technology in support of the International Thermonuclear Experimental Reactor (ITER) and other major international fusion experiments. However, the closure of domestic fusion research facilities and the failure either to upgrade or to start new medium-scale experiments, together with substantially decreased funding to fusion nuclear science and technology research, creates concern as to whether the United States will continue to be a scientific leader in the field.

BURNING PLASMA SCIENCE

U.S. fusion scientists and engineers have contributed a substantial number of new, innovative ideas to the study of burning plasma science, including the following examples.

Theory and Simulation to Understand and Predict Burning Plasma Dynamics

The U.S. Department of Energy (DOE) Office of Fusion Energy Sciences (FES) theory and simulation program is organized into a base program, including several Scientific Discovery through Advanced Computation (SciDAC) centers[2] focused on developing advanced simulation capabilities. U.S. scientists are recognized internationally as leading the world both in basic theory and in simulation. For example, U.S. researchers led important efforts in understanding multi-scale turbulent transport,[3,4,5] energetic particle physics,[6] and pedestal physics.[7] Many of the most widely employed simulation codes and physics models have been developed within the U.S. theory and simulation program. A recent workshop collaboratively sponsored by the DOE Office of Advanced Scientific Computing Research and DOE/FES documented the status, codes, opportunities, and challenges of

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[1] National Research Council (NRC), *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[2] Current fusion SciDAC centers are listed online, with research focus on edge physics, multiscale integrated modeling, and materials science (http://www.scidac.gov/fusion/fusion.html).

[3] Ku, Chang, and Diamond, Full-f gyrokinetic particle simulation of centrally heated global ITG turbulence from magnetic axis to edge pedestal top in a realistic tokamak geometry, *Nuc Fusion* 49:115021, 2009.

[4] Howard et al., Multi-scale gyrokinetic simulation of tokamak plasmas: Enhanced heat loss due to cross-scale coupling of plasma turbulence, *Nuc Fusion* 56:014004, 2015.

[5] N.T. Howard et al., Multi-scale gyrokinetic simulations of an alcator C-Mod, ELM-y H-mode plasma, *Plasma Phys. Control. Fusion* 60:014034, 2018.

[6] Fasoli et al., Physics of energetic ions, *Nuc Fusion* 47:S264-S284, 2007.

[7] Ferraro, Jardin, and Snyder, Ideal and resistive edge stability calculations with M3D-C-1, *Phys Plasmas* 17:102508, 2010.

integrated simulations for magnetic fusion energy sciences.[8] In recent years, understanding of key areas such as coupled core/pedestal transport and stability has advanced to the point where detailed predictions can be made in advance of experiments. Indeed, new high-performance regimes of operation have been predicted and later observed in experiments motivated directly by theoretical predictions.[9] These same predictive tools have been employed to develop high-performance scenarios for ITER and other planned devices.[10] The capability exists to use theoretical understanding to optimize devices and achieve higher performance. While the U.S. theory program is focused primarily on tokamak research, key innovations have also been developed in other areas, such as the idea of quasi-symmetry in stellarators to reduce transport.[11]

Exascale computing platforms present great opportunities for computational physics.[12] The increased computing power should allow researchers to investigate new and previously inaccessible problems in burning plasma science.[13] Equally important, exascale computing should greatly improve the community's ability to understand and predict experiments with validated sophisticated numerical models. Exascale computing can substantially improve our understanding of burning plasma physics and guide experiment planning, but computation will not be a substitute for actually building and carrying out experiments needed to validate models, even at the exascale. Fusion energy simulations[14] have been selected as an application area of the new Exascale Computing Project, a collaborative effort of the DOE Office of Science and the National Nuclear Security Administration.

Medium-Scale Fusion Research Facilities

Until the end of fiscal year (FY) 2016, the United States supported three medium-scale experimental facilities: the DIII-D tokamak at General Atomics in San Diego, the National Spherical Torus Experiment-Upgrade (NSTX-U) located at PPPL, and the Alcator C-Mod high-field tokamak at the Massachusetts Institute of Technology (MIT). Descriptions of these three facilities are given, for example, in the DOE FY2016 Congressional Budget Request (pp. 137-138).[15] The DIII-D tokamak began operation in 1986. The DIII-D research goal is to "establish the scientific basis to optimize the tokamak approach to magnetic confinement fusion"[16] through the exploration of plasma control techniques and conditions scalable to ITER and future fusion reactors. NSTX-U is a low-aspect ratio tokamak designed to assess the spherical tokamak as a possible fusion neutron source, study the plasma-material interface, and advance toroidal confinement physics. NSTX-U is an upgrade of the NSTX experiment that operated from 1999 to 2011. NSTX-U was dedicated in May 2016 but is now undergoing repairs and is not presently operating. The Alcator C-Mod tokamak began operation in 1991. C-Mod is a compact tokamak using strong magnetic fields to confine high-pressure plasma in a small volume. The compact size and high magnetic field of the Alcator C-Mod tokamak allow operation at and above the ITER design values for magnetic field and plasma density, and it has all-metal walls that experience heat fluxes approaching those projected for ITER. As a consequence of the DOE/FES 2013 decision to reduce domestic fusion research, the operation of the Alcator C-Mod tokamak ended in October 2016,[17] immediately following experiments that set the world's record for volume-

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[8] U.S. Department of Energy (DOE), *Integrated Simulations for Magnetic Fusion Energy Sciences,* Report from the DOE Workshop held June 2-4, 2015, Washington, D.C.

[9] Snyder et al., Super H-mode: Theoretical prediction and initial observations of a new high-performance regime for tokamak operation, *Nuc Fusion* 55:083026, 2015.

[10] Snyder et al., A first-principles predictive model of the pedestal height and width: Development, testing and ITER optimization with the EPED model, *Nuc Fusion* 51:103016, 2011.

[11] Xanthopoulos et al., Controlling turbulence in present and future stellarators, *Phys Rev Lett* 113:155001, 2014.

[12] DOE, *Scientific Grand Challenges: Fusion Energy Science and the Role of Computing at the Extreme Scale,* Report from the DOE Workshop held March 18-20, 2009, Washington, D.C.

[13] DOE, *Integrated Simulations for Magnetic Fusion Energy Sciences,* Report from the DOE Workshop held June 2-4, 2015, Washington, D.C.

[14] See https://www.exascaleproject.org/pppl-physicists-win-ecp-funding/.

[15] DOE, FY2016 Congressional Budget Request for Fusion Energy Sciences, Office of Science, Washington, D.C., 2015, p. 137-138.

[16] See https://science.energy.gov/fes/research/advanced-tokamak/.

[17] *MIT News*, Alcator C-Mod tokamak nuclear fusion reactor sets world record on final day of operation, October 14, 2016, https://phys.org/news/2016-10-alcator-c-mod-tokamak-nuclear-fusion.html.

averaged plasma pressure contained within a magnetically confined fusion device. Many of the significant accomplishments noted in Chapter 3 resulted from pioneering experiments conducted using these three medium-scale facilities.

In addition to mid-scale research facilities, the U.S. fusion energy sciences program provided about 1.6 percent (approximately $7 million) of the FY2016 budget[18] to operate small exploratory experiments, primarily at universities, in support of foundational burning plasma research and long-pulse burning plasma research.

Proposals for new facilities and facility upgrades were recommended by the 2013 Fusion Energy Sciences Advisory Committee (FESAC) Subcommittee on the Prioritization of Proposed Scientific User Facilities[19] and by the 2014 FESAC Subcommittee on Strategic Planning.[20] These U.S. facility initiatives included major upgrades to the DIII-D and NSTX-U experiments and plans for construction of a Fusion Nuclear Science Facility. Additionally, the Advanced Divertor Experiment was proposed as an upgrade to the Alcator C-Mod facility at MIT.[21]

A strength of the U.S. program is the close coupling between theoretical and experimental research. Owing to their excellent diagnostics and flexibility, medium-scale facilities are well suited to test and validate experimental models. These validated models are beginning to provide the ability to predict new, and potentially more attractive, operating regimes.

The current U.S. fusion research strategy has an increasing focus on U.S. participation in newer international long-pulse experiments with superconducting magnets including EAST (China),[22] KSTAR (Republic of Korea),[23] and Wendelstein 7-X (Germany).[24] EAST began operation in 2006 and KSTAR began in 2009. The Wendelstein 7-X stellarator began operation in December 2015, requiring €350 million for the stellarator device[25] and additional amounts for personnel and materials during construction. The HL-2M tokamak is under construction at the Southwestern Institute of Physics[26] as an upgrade to the existing HL-2A[27] device. HL-2M will have higher plasma heating power and magnetic field strength to explore higher-pressure, fusion-relevant plasma. The JT-60SA tokamak in Japan is under construction as a Japan-Europe project and is expected to begin operation in 2020.[28] Non-U.S. proposals for new facilities include the superconducting Divertor Tokamak Test facility[29] that would be built by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development's fusion laboratory in Frascati, Italy, and the China Fusion Engineering Test Reactor[30] under consideration as a new fusion facility to demonstrate self-sufficient tritium breeding. While researchers in the U.S. fusion community welcome these international opportunities, presentations to the committee[31] and during the first fusion community workshop[32]

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[18] DOE, FY2016 Congressional Budget Request for Fusion Energy Sciences, Office of Science, 2015, p. 137-138.

[19] DOE, *Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science*, Fusion Energy Sciences Advisory Committee, Washington, D.C., March 21, 2013.

[20] DOE, *Report on Strategic Planning: Priorities Assessment and Budget Scenarios*, Fusion Energy Sciences Advisory Committee, Washington, D.C., December 2014.

[21] LaBombard et al., ADX: A high field, high power density, advanced divertor and RF tokamak, *Nuc Fusion* 55:053020, 2015.

[22] Wu, An overview of the EAST project, *Fusion Eng and Design* 82:463, 2007.

[23] Oh et al., Commissioning and initial operation of KSTAR superconducting tokamak, *Fusion Eng and Design* 84:344, 2009.

[24] Bosch et al., Final integration, commissioning and start of the Wendelstein 7-X stellarator operation, *Nuc Fusion* 57:116015, 2017.

[25] See http://www.ipp.mpg.de/4010154/02_16.

[26] Liu et al., Assembly study for HL-2M tokamak, *Fusion Eng Design* 96-97:298-301, 2015.

[27] Duan et al., Overview of recent HL-2A experiments, *Nuc Fusion* 57:102013, 2017.

[28] Shirai, Barabaschi, and Kamada, Progress of JT-60SA Project: EU-JA joint efforts for assembly and fabrication of superconducting tokamak facilities and its research planning, *Fusion Eng and Design* 109:1701, 2016.

[29] Crisantia et al., The Divertor Tokamak Test facility proposal: Physical requirements and reference design, *Nuc Materials and Energy* 12:1330, 2017.

[30] Song et al., Concept design of CFETR tokamak machine, *IEEE Trans Plasma Sci* 42:503, 2014.

[31] See, for example, Stewart Prager, A reinvigorated US fusion energy program, presented to the Committee for a Strategic Plan for U.S. Burning Plasma Research, August 29, 2017.

[32] See, for example, T. Carter, R. Fonck, M. Haynes, D. Maurer, D. Meade, G. Navratil, S. Prager, G. Tynan, D. Whyte, "Perspectives on a Restructured US Fusion Energy Research Program," presented to the Workshop on U.S. Magnetic Fusion Research Strategic Directions, July 24, 2017.

did not foresee how international cooperation by itself will allow the U.S. fusion researchers to maintain a world leadership position without new facility starts within the United States.

FUSION TECHNOLOGY AND ENGINEERING SCIENCE

Many of the program contributions to burning plasma science are interrelated to advancements in fusion technology and engineering science. The Virtual Laboratory for Technology (VLT) functions as a “virtual” laboratory with 18 collaborating institutions within the United States, including eight universities, nine national laboratories, and one private company.[33] The VLT facilitates fusion technology and engineering science in the United States by (1) developing the enabling technology for existing and next-step experimental devices, (2) exploring and understanding key materials and technology feasibility issues for attractive fusion power sources, and (3) conducting advanced design studies that provide integrated solutions for next-step and future fusion devices and call attention to research opportunities in the field.[34]

Since the 2004 NRC Burning Plasma Assessment report,[35] fusion technology advances have been driven by ITER research needs and by next-step goals to fully enable the fusion energy system. Key contributions from the U.S. fusion technology program are fusion fuel cycle, fusion materials, fusion materials modeling,[36] fusion plasma power handling, superconducting magnets, and liquid metals. These contributions have resulted from joint international projects in support of ITER and from tasks directed by U.S. researchers. Examples include vacuum and gas species management,[37,38] tritium fusion fuel cycle development,[39] pellet injection for fueling and disruption mitigation,[40] and the manufacture of the ITER central solenoid.[41] The United States has made significant advancements in fusion materials studies, including contributing to the qualification of reduced activation ferritic martensitic steels for the European demonstration fusion reactor,[42] nanostructured[43] and oxide dispersed strengthened steels,[44] all aspects of SiC/SiC technology,[45] and new understanding of tungsten[46] and tungsten composites[47] as fusion plasma-facing materials. Linear plasma simulators allow for long-duration study of material

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[33] Phil Ferguson, “Response to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research,” presented to the Committee for a Strategic Plan for U.S. Burning Plasma Research, August 29, 2017. See also http://vlt.ornl.gov/.

[34] C.C. Baker, An overview of enabling technology research in the United States, *Fusion Engineering and Design* 61-62:37-45, 2002.

[35] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[36] Wirth, Hammond, Krasheninnikov, and Maroudas, Challenges and opportunities of modeling plasma’s surface interactions in tungsten using high-performance computing, *J Nucl Mater* 463:30, 2015.

[37] Duckworth et al., Development and demonstration of a supercritical helium-cooled cryogenic viscous compressor prototype for the ITER vacuum system, *Adv Cryogenic Eng* 57A-B:1234-1242, 2012.

[38] Perevezentsev et al., Study of outgassing and removal of tritium from metallic construction materials of ITER vacuum vessel components, *Fusion Sci and Technology* 72:1-16, 2017.

[39] Klein, Poore, and Babineau, Development of fusion fuel cycles: Large deviations from US defense program systems, *Fusion Eng Des* 1, 2015.

[40] Lyttle et al., Tritium challenges and plans for ITER pellet fueling and disruption mitigation systems, *Fusion Sci and Tech* 71:251, 2017.

[41] Libeyre, P., Cormany, C., Dolgetta, N. et al., Starting manufacture of the ITER central solenoid, *IEEE Trans on Applied Superc* 26:4203305, 2016.

[42] Stork et al., Developing structural, high-heat flux and plasma facing materials for a near-term DEMO fusion power plant: The EU assessment, *J Nuc Materials* 455:277-291, 2014.

[43] Parish et al., Helium sequestration at nanoparticle-matrix interfaces in helium plus heavy ion irradiated nanostructured ferritic alloys, *J. Nuc. Materials* 482:21, 2017.

[44] Zinkle et al., Development of next generation tempered and ODS reduced activation ferritic/martensitic steels for fusion energy applications, *Nuc Fusion* 57:092005, 2017.

[45] Snead et al., Silicon carbide composites as fusion power reactor structural materials, *J Nuc Materials* 417:330, 2011.

[46] Baldwin and Doerner, Helium induced nanoscopic morphology on tungsten under fusion relevant plasma conditions, *Nuc Fusion* 48:035001, 2008.

[47] Garrison et al., Irradiation effects in tungsten-copper laminate composite, *J Nuc Materials* 481:134, 2016.

evolution under fusion-relevant plasma flux, but they are not useful to test integrated plasma-material effects expected in fusion divertors. In the United States, linear plasma simulators include the PISCES facility at University of California, San Diego,[48] the Tritium Plasma Experiment at Idaho National Laboratory (INL),[49] and the recently completed Material Plasma Exposure Experiment at Oak Ridge National Laboratory.[50] The STAR[51] facility, part of the Fusion Safety Program at INL, has unique experimental capabilities that have been used to develop the only fusion safety code accepted by the French authorities for ITER licensing, the INL fusion-modified MELCOR code.[52,53]

The United States has also made progress in the areas of (1) fusion nuclear systems study, leading to the definition of requirements for a Fusion Nuclear Science Facility[54] for integrated testing of fusion components, and (2) experiments and massively parallel simulations to understand magnetohydrodynamic flows of liquid metal, self-cooled, dual-coolant, and helium-cooled lead lithium blanket concepts at the University of California, Los Angeles, Magnetohydrodynamic PbLi Experiment facility.[55] This effort is well recognized by the international fusion and magnetohydrodynamics communities for its potential to serve a central role in U.S. and international programs on blankets and plasma-facing components.

Although there have been significant advances in U.S. capabilities since the 2004 NRC report, many research needs for fusion technology and engineering science remain unresolved. These include fusion plasma material interactions, fusion blanket materials, fuel cycle safety, breeding and fueling, and opportunities for advanced materials and manufacturing guided by new high-performance computing tools.

U.S. RESEARCH AND PARTICIPATION IN INTERNATIONAL FUSION ACTIVITIES

Fusion energy research is international. The United States participates actively in Europe and Asia, and international scientists from around the world participate in fusion experiments and research programs within the United States. Many advancements in all key topical areas of fusion research are published collaboratively with international co-authors. The International Tokamak Physics Activity (ITPA) provides an international framework for coordinated fusion research; since 2008, the ITPA operates under the auspices of ITER. [56]

U.S. Participation in Fusion Activities in Europe

The United States has made and continues to make important contributions to the world's largest currently operating fusion device, Joint European Tours (JET). This includes involvement in testing important auxiliary systems relevant to ITER (e.g., the ITER-like Shattered Pellet Injector[57]), plasma diagnostics (e.g., Faraday cups),

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[48] Tynan et al., Mixed material plasma-surface interactions in ITER: Recent results from the PISCES Group, in *Plasma Interaction in Controlled Fusion Devices* (Benkadda, ed.), *AIP Conference Proceedings* 1237, pp. 78-91, 2010.

[49] Shimada et al., Tritium plasma experiment upgrade and improvement of surface diagnostic capabilities at STAR facility for enhancing tritium and nuclear PMI sciences, *Fus Sci and Technology* 71:310, 2017.

[50] Rapp et al., The development of the material plasma exposure experiment, *IEEE Trans Plasma Sci* 44:3456, 2016.

[51] Tynan et al., Mixed material plasma-surface interactions in ITER: Recent results from the PISCES Group, in *Plasma Interaction in Controlled Fusion Devices* (Benkadda, ed.), AIP Conference Proceedings 1237, pp. 78-91, 2010.

[52] Merrill et al., Modifications to the MELCOR code for application in fusion accident analyses *Fusion Eng Design* 51-52:555-563, 2000.

[53] Taylor et al., Updated safety analysis of ITER, *Fusion Eng Design* 86:619-622, 2011.

[54] C.E. Kessel et al., The Fusion Nuclear Science Facility, the critical step in the pathway to fusion energy, *Fusion Science and Technology* 68:225-236, 2015, doi: 10.13182/FST14-953.

[55] Smolentsev et al., Review of recent MHD activities for liquid metal blankets in the US, *Magnetohydyamics* 53:411, 2017.

[56] See https://www.iter.org/org/team/fst/itpa.

[57] Baylor et al., Disruption-mitigation-technology concepts and implications for ITER, *IEEE Trans Plasma Sci* 38:419, 2010.

experimental operating scenarios (e.g., involvement in developing deuterium-tritium scenarios[58]), and simulation codes (e.g., TRANSP[59]). Additionally, simulation codes developed by U.S. scientists have been adopted by international partners and are now routinely used for scenario modeling within the JET program and across EUROfusion ITER-related activities. Since 2016, 9 of the 33 articles appearing in the International Atomic Energy Agency (IAEA) journal *Nuclear Fusion* and reporting results from the JET device involved co-authors from the United States.

For medium-sized tokamaks (ASDEX Upgrade, Germany; TCV, Switzerland; MAST Upgrade, United Kingdom), many bilateral collaborations exist between the United States and EU partners. Prominent recent examples of U.S. contributions include temporarily moving diagnostic devices from U.S. facilities to EU machines and joint experiments on multiple machines to develop understanding and robust demonstration of control schemes and new plasma scenarios. Since 2016, about 10 percent of the articles appearing in *Nuclear Fusion* describing research with these medium-sized tokamaks involved co-authors from the United States.

Another important U.S. contribution to fusion research in the EU has been the participation in the Wendelstein 7-X stellarator project. This includes the construction and operation of five large auxiliary coils[60] (installed on the outside of the device to assist in precise setting of the magnetic fields at the plasma edge) and an X-ray spectrometer, as well as the development of fluctuation diagnostics and a pellet injector. This work is carried out at three U.S. national laboratories (Princeton, Oak Ridge, and Los Alamos) and three U.S. universities (Auburn University, University of Wisconsin, Madison, and MIT), supporting Wendelstein 7-X with equipment that has been funded, designed, and produced in the United States and with related magnetic field and plasma diagnosis and modeling. Since 2016, more than half of the articles appearing in *Nuclear Fusion* describing research with the Wendelstein 7-X stellarator involved co-authors from the United States.

U.S. Participation in Fusion Activities in Asia

The United States is actively playing a significant role in developing new fusion programs in Asia. Major contributions have been made to the programs on new Asian devices since the 2004 NRC report, notably in EAST (China), KSTAR (Republic of Korea), HL-2A (China), and J-TEXT (Japan), and a strong relationship continues with smaller spherical tokamaks (QUEST at Q-shu University, Japan; VEST at Seoul National University, Republic of Korea; SUNIST at Tsinghua University, China). One major focus of this international partnership has been in the use of long-pulse superconducting devices to develop steady-state plasma scenarios.[61] As an example, collaborations on EAST have made advances in plasma control and wall conditioning techniques developed collaboratively with and initially demonstrated on DIII-D. Novel computer science hardware and software infrastructure has improved data movement, visualization, and communication and allow scientists in the United States to remotely conduct experiments using the EAST facility.[62] In July 2017, the Chinese researchers using EAST achieved a stable 101.2-second steady-state high confinement plasma, setting a world record in long-pulse H-mode operation.[63]

Recent U.S.-Asia cooperation is also seen in the development of HL-2M under construction in China and in the physics design of CFETR burning plasma facility under consideration in China, where the United States provides design expertise and simulation codes.[64]

U.S. Participation in the International Tokamak Physics Activity

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[58] Budny et al., Predictions of H-mode performance in ITER, *Nuc. Fusion* 48:075005, 2008.

[59] Budny, Cordey, TFTR Team, and JET Contributors, Core fusion power gain and alpha heating in JET, TFTR, and ITER, *Nuc Fusion* 56:056002, 2016.

[60] Lazerson et al., Error field measurement, correction and heat flux balancing on Wendelstein 7-X, *Nuc Fusion* 57:046026, 2017.

[61] See, for example, Garofalo et al., Development of high poloidal beta, steady-state scenario with ITER-like tungsten divertor on EAST, *Nuc Fusion* 57:076037, 2017.

[62] D.P. Schissel et al., Remote third shift EAST operation: A new paradigm, *Nucl. Fusion* 57:056032, 2017.

[63] See https://phys.org/news/2017-07-china-artificial-sun-world-steady-state.html.

[64] See, for example, Chen et al., Self-consistent modeling of CFETR baseline scenarios for steady-state operation, *Plasma Phys Controlled Fusion* 59:075005, 2017.

The International Tokamak Physics Activity (ITPA) began operating in 2001 with urging by the United States and under the auspices of the IAEA International Fusion Research Council. Since 2008, ITPA operates under the auspices of ITER. The ITPA provides an international framework for coordinated fusion research useful for all fusion programs and for broad progress toward fusion energy. The United States continues to make significant contributions to the ITPA, which coordinates the international tokamak physics research and development activities and provides the physics basis for the ITER project. Presently, the United States chairs four of the seven ITPA topical working groups. The United States also actively participates in multiple-facility, joint tokamak experimental exercises. Until recently, these joint experiments used the C-Mod, NSTX-U, and DIII-D tokamaks in the United States for dedicated studies and coordinated analysis in support of international joint experiments. For example, joint experiments coordinated among MAST, ASDEX Upgrade, and DIII-D have recently evaluated the use of resonant magnetic field perturbations and pellet injection to suppress edge localized modes (ELMs).[65] These joint experiments are in general agreement with plasma response modeling, confirm that magnetic perturbations can limit ELMs, and have led to a change in the ITER design to introduce ELM control systems. Since the end of Alcator C-Mod operation, the United States is no longer able to provide scientific support to ITER in the area of tokamak operation and physics in fusion devices with reactor-relevant metallic walls.

International Participation in the U.S. Program

International fusion researchers from the ITER partnership also collaborate in the U.S. research effort. International collaboration with U.S. researchers in burning plasma science involves all parts of the program, including use of experimental facilities and involvement with theory, simulation, and modeling groups. Since 2016, of those articles appearing in the IAEA journal *Nuclear Fusion* describing research with U.S. medium-sized tokamaks, one-fourth involved co-authors from Europe and one-fourth involved co-authors from Asia. Half of all articles appearing in *Nuclear Fusion* since 2016 reporting advancements in fusion simulation involved collaborating international co-authors. In the area of fusion technology and engineering science, the EUROfusion Work Package for Plasma Facing Components pays to use the PISCES-B facility at University of California, San Diego, helping to identify first wall materials for ITER and future fusion energy systems. Currently, no other linear plasma facility is capable of performing experiments with beryllium samples. One main goal of this collaboration is to study the interaction between deuterium or helium plasmas with beryllium and tungsten surfaces. Another example is the study of high dose irradiation effects in a U.S.-Japan collaboration in an experiment with more than 8 years of irradiation on the High Flux Isotope Reactor at Oak Ridge National Laboratory.

THE ROLE OF ITER IN TODAY'S U.S. BURNING PLASMA RESEARCH ACTIVITIES

As stated in the DOE Office of Science *Ten-Year Perspective* (2015) (p. 8), "the global magnetic fusion research community is focused primarily on the commencement of the 'burning plasma' era." This global focus is reflected in the U.S. fusion energy science research program. The three fusion research directions, "burning plasma science: foundations," "burning plasma science: long pulse," and "burning plasma science: high power," advance the plasma science, computational science, and materials science in support of burning plasma research that will be conducted on the ITER device. Research objectives of the DOE *Ten-Year Perspective* include "urgent scientific questions—such as how to control transient events—required for ITER to meet needs of the ITER project," validating predictive models for "formulating ITER operational scenarios," and understanding how to confine and control long-pulse fusion plasmas as "essential expertise for U.S. scientists who may participate in research operations on ITER and future burning plasma experiments."[66]

Planning for U.S. participation in the ITER program began in 2006 by the United States Burning Plasma Organization (USBPO) at the request of DOE/FES in response to a requirement of the Energy Policy Act of 2005.[67]

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[65] Liu et al., Comparative investigation of ELM control based on toroidal modelling of plasma response to RMP fields, *Phys Plasmas* 24:056111, 2017.

[66] DOE, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, Washington, D.C., December 2015.

[67] U.S. Burning Plasma Organization, *Planning for the U.S. Fusion Community Participation in the ITER Program*, June 2006, https://www.burningplasma.org/web/ReNeW/EPAct_final_June09.pdf.

This plan was endorsed by the 2009 NRC Committee to Review the U.S. ITER Science Participation Planning Process.[68] The 2009 NRC report further stated (p. 2), "U.S. involvement in developing the research program for ITER will be crucial to the realization of U.S. fusion research goals."

The USBPO serves the U.S. fusion research community and coordinates burning plasma research through open membership in topical groups. Leaders of each topical group coordinate research to address priority scientific issues and provide contact to the international burning plasma research with the ITPA and with the ITER organization. The director and deputy director of the USBPO explained to the committee[69] that burning plasma research in support of the ITER project has resulted in significant progress in many key areas, including transient events, plasma material interactions, integrated simulations, operating scenarios, heating and current drive, diagnostics, plasma control, energetic particles, and transport and confinement, and these advancements "have only increased our readiness to take the burning plasma step."

Research in support of ITER has facilitated enhanced multi-national collaborative activities (experiments and analysis) through the ITER-sponsored ITPA topical groups. As reported earlier in this chapter, U.S. scientists collaborate with Asian research programs with superconducting tokamaks, EAST and KSTAR. This collaboration targets the development of long-pulse, high-performance operating scenarios with acceptable heat exhaust that are target scenarios for ITER operation.

Additionally, because the vast majority (approximately 80 percent) of U.S. ITER construction funding remains within the U.S. supply chain,[70] participation in ITER has resulted in significant advances in U.S. domestic industrial capabilities and capacities that would not have happened without ITER participation. For example,

- The United States has proven its capacity for fabricating superconductor in bulk, producing over four miles of cable-in-conduit superconductor for the toroidal field magnets;
- The United States is fabricating a first-of-a-kind 13 m tall, 13 T central solenoid electromagnet, which is unique worldwide and has required the development of bespoke fabrication and testing infrastructure;
- U.S. industry is developing microwave and radio-frequency transmission lines to provide unprecedented power transfer for heating in ITER;
- High-throughput cryogenic pellet fueling systems and tritium processing systems have been developed by U.S. national laboratories; and
- A wide array of instrumentation for harsh nuclear environments has been developed in the U.S. supply chain.

The United States has also been a key contributor towards the approval of ITER's license to start construction, by providing a "pedigreed" version of the fusion-modified safety code MELCOR, developed and maintained by the Fusion Safety Program at INL, that has been used extensively for the safety analyses presented to the French Nuclear Regulator (Autorité de Sureté Nucléaire) as part of the Construction Authorization Request.

Of course, in addition to ITER's role as a focus of both the international and U.S. research programs, the United States has committed to contributing 9.09 percent of ITER's construction costs. According to the DOE project execution plan for ITER,[71] the United States has "made considerable progress in completing its assigned hardware design, R&D, and fabrication work." Final design of about two-thirds of U.S. hardware is complete, and 2 of 13 in-kind hardware systems have been delivered. A total of $942 million has been obligated by the U.S. ITER project with contracts spread across U.S. industry, universities, and national laboratories, across 44 states.[72] The technical leadership and contributions made by the U.S. fusion science team is and will continue to be important to the eventual success of the ITER design, operation, diagnostics, and analyses. In addition, the U.S. financial

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[68] NRC, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, Washington, D.C., 2009.

[69] Charles Greenfield and Amanda Hubbard, Perspectives on Burning Plasma Research, presented to the Committee for a Strategic Plan for U.S. Burning Plasma Research, June 5, 2017.

[70] Ned R. Sauthoff, Perspectives from the US ITER Project, presented to the Committee for a Strategic Plan for U.S. Burning Plasma Research, August 29, 2017.

[71] DOE, *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, Office of Science, Fusion Energy Sciences, Washington, D.C., January 2017.

[72] See slides 56-59 in Ned Sauthoff's presentation to the committee, August 29, 2017, Ref. 23.

commitment is highly leveraged by the sharing of costs and technology with its international partners. The performance of the United States in its ITER obligations has been very favorably assessed by the U.S. Government Accountability Office[73] and DOE assessments and quality assurance audits conducted in 2015.

As President George W. Bush announced, ITER is “the largest and most technologically sophisticated fusion experiment in the world” and “critical to the development of fusion as a viable energy source.” Because burning plasma research in support of ITER and in preparation for ITER experiments is a primary focus of the international and U.S. research programs, ITER is more than a construction project. ITER plays a central role in today’s U.S. burning plasma research activities, and participation in the ITER project provides formal mechanisms for U.S. scientists to take leading roles in the international effort to develop fusion energy.

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[73] U.S. Government Accountability Office, *FUSION ENERGY: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor*, Report to Congress, GAO-14-499, Washington, D.C., June 2014.

5

Assessments

In this interim report, the Committee on a Strategic Plan for U.S. Burning Plasma Research makes the following assessments of the importance of burning plasma research to the development of fusion energy and of the current status of U.S. burning plasma research, including current and planned participation in international activities. These seven assessments are also the summary of this interim report.

Assessment 1: Burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components.

All efforts to make fusion energy require a burning plasma—an ionized gas like the Sun and stars that is heated by fusion reactions. Burning plasma research begins with understanding, measuring, and predicting the complex physical processes of the plasma and of the energetic particles moving within the plasma created by fusion reactions. Next, burning plasma research includes the high-technology tools used to control, confine, and heat the plasma to very high temperature and pressure. Finally, burning plasma research embodies the applied and engineering sciences necessary to design reliable structures that surround the plasma and convert fusion energy into useful heat and power. Burning plasma research is interdisciplinary and results in technological and scientific achievements that touch many aspects of everyday life and lead to new insights in related fields such as optics, fluid mechanics, and astrophysics.

Although significant fusion power has been generated for short periods in the laboratory (4 MW for 4 s and up to 16 MW for shorter periods) and some processes expected in a burning plasma have been studied at the temperatures and pressures required for fusion energy, a burning plasma, which is heated predominately by fusion reactions, has never been created. This requires construction of a burning plasma experiment such as the International Thermonuclear Experimental Reactor (ITER). A burning plasma experiment will allow integrated investigation of the burning plasma with the advanced technology magnetic fusion schemes require. Because of its large size and complexity, constructing a burning plasma experiment leads to advancements in industrial capability, such as for large superconducting magnets, vacuum technologies, complex cryogenic systems, ultra-precise construction, and robotic systems to handle materials.

Assessment 2: The U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.

Experiments conducted using research facilities in the United States have been highly productive. New ideas to control and sustain burning plasma have been discovered, and theoretical and computational models developed in the United States have substantially improved the ability to control plasma stability, predict plasma confinement, and enhance fusion energy performance. The understanding of burning plasma science has advanced significantly, including such critical topics as the transport of heat and particles by multi-scale turbulence, the behavior of energetic particles produced by fusion reactions, and the physics of the narrow insulating layer at the plasma edge (or "pedestal"). In addition, new techniques have been developed to avoid and mitigate transient events, which can erode plasma-facing materials. Scenarios of burning plasma operation have been developed experimentally and explored with computational models that are expected to simultaneously satisfy the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components. These scenarios further increase confidence in the burning plasma performance that can be achieved in ITER. While important avenues for further exploration remain, current understanding increases confidence in ITER achieving its scientific mission. The widely recognized importance of U.S. research contributions to the field also supports the expectation that, if the United States continues to participate in ITER, scientists within the United States will make leading contributions to the study of fusion energy at the power plant scale.

Assessment 3: Construction and operation of a burning plasma experiment is a critical, but not sufficient, next step toward the realization of commercial fusion energy. In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.

A burning plasma experiment will examine for the first time many of the interconnected scientific and technology issues that must be addressed to produce magnetic fusion energy. Among these are the experimental validation of theoretical predictions related to plasma stability, plasma heating, transport of plasma heat and particles, alpha particle physics from fusion reactions, and disruption avoidance for tokamaks in substantially unexplored regimes of magnetic confinement. Equally important are gains in fusion engineering science including large-scale superconducting magnet technology, progress toward understanding fusion blanket science, tritium science and management, remote handling of materials and components, and large-scale systems integration. As a burning plasma experiment, ITER is a critical step along the path to advance the science and technology of a fusion power source. Still, ITER is a fusion research facility and a long way from being a system for commercial power. In a commercial system, economics requires the thermal power to increase about seven-fold. Continuous operation requires efficient coupling of radio waves into the plasma to sustain the plasma current. Challenging plasma-wall problems need inventive solutions in order to safely handle the flux of energetic neutrons on the inner wall and the escaping heat from the plasma that is directed onto the plates of a protective divertor. The self-consistent production and safe handling of tritium will not be fully addressed in ITER but must be solved for commercial fusion power. Lastly, the expected gains in engineering and economics that might accrue from technology and materials innovations, like the newly developed rare-earth, high-temperature superconductors, need to be investigated; however, these innovations will only impact fusion facilities built beyond ITER. The overall picture is that a burning plasma experiment, such as ITER, will lead to major gains along the path to fusion energy while other fusion energy experiments will need to address remaining science and technology challenges and demonstrate innovative solutions that lead to a reduced size, lower cost, full-scale power source.

Assessment 4: Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.

Since the National Research Council's (NRC's) study in 2004,[1] strategic plans leading to a fusion energy demonstration have been developed by many of our international partners, all with high-level governmental support and in some cases even adopted federal legislation. These strategies all recognize that the burning plasma regime provided by ITER is the most expedient way to demonstrate controlled fusion on commercial scale, but importantly, also elucidate the accompanying research and technology programs needed to progress beyond ITER to a commercial fusion reactor. Such strategic planning guides the national research and innovation programs, helps to engage industrial partners and sets the national priorities of our partners, enabling them to develop key areas of unique expertise. The absence of such a nationally endorsed strategic plan for delivery of fusion energy in the United States inhibits the long-term planning of all participants in the fusion endeavor in the United States, from universities, to national laboratories, to industrial partners. Without a long-term plan, the United States risks being overtaken as our partners advance the science and technology required to deliver fusion energy. Conversely, the adoption of such a plan has the potential to support strategic funding decisions and priorities within the national program and help foster innovation to drive towards commercially viable fusion reactor designs.

Assessment 5: Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.

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[1] National Research Council (NRC), *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

As reported by the NRC Burning Plasma Committee in 2004,[2] many of the scientific and technical issues of importance to the long-range development of fusion are best addressed by research facilities having size and complexity much smaller than that needed for a burning plasma experiment. A long-term strategy for fusion energy benefits from a domestic effort in parallel with the ITER project focused on developing the scientific base for promising fusion reactor concepts and technologies.

However, during the past decade, various programmatic decisions have closed domestic experimental facilities without opportunities for new starts and without compensating programs internationally. In 2005, the budget for U.S. fusion technology efforts was sharply reduced. In 2013, the Department of Energy's Office of Fusion Energy Sciences implemented an overall reduction in the domestic program while making only a modest increase in funding for scientific collaborations on non-U.S. experimental facilities. Currently, only one mid-scale fusion experiment is operating in the United States. Mid-scale experimental facilities can attract talent to the field, provide broad scientific and engineering opportunities, and test innovations that could improve the fusion energy concept and strengthen U.S. expertise in fusion science and technology.

Assessment 6: Any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary for such an inherently large project. A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.

Past studies of magnetic fusion energy research recommended U.S. entrance into international partnerships as the most cost-effective approach to undertake large fusion energy experiments. These studies include *Cooperation and Competition on the Path to Fusion Energy*,[3] *Pacing the U.S. Magnetic Fusion Program*,[4] the 1995 report of the President's Committee of Advisors on Science and Technology Panel on U.S. Fusion R&D Programs,[5] and *Realizing the Promise of Fusion Energy*.[6] After considering various options for a burning plasma experiment, the 2004 NRC Burning Plasma Assessment Committee[7] recommended that the United States should participate in ITER. But, if the United States were not to participate in ITER, the committee also recommended the pursuit of international partnership in an alternate burning plasma experiment. A burning plasma experiment at the scale of a power plant is necessarily a large facility and integrates multiple advanced technologies. At the present time, no country has the combination of scientific and engineering expertise, industrial capacity, and long-term national commitment to undertake this critical task alone.

While previous studies concluded that fusion energy research substantially benefits from international cooperation, they also described a potential for failure if international partners were unable to meet their commitments. The NRC's report *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*[8] recommended that steps should be taken to "seek greater funding stability for the international ITER project to ensure that the United States remains able to influence the developing ITER research program, to capitalize on research at ITER to help achieve U.S. fusion energy goals, to participate in obtaining important scientific results on burning plasmas from ITER, and to be an effective participant in and beneficiary of future international scientific collaborations."

The committee has reviewed the recommendations from these past studies in the context of the existing ITER partnership, the assessments of U.S. burning plasma research listed above, and the benefits international

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[2] Ibid.

[3] National Research Council (NRC), *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, 1984.

[4] NRC, *Pacing the U.S. Magnetic Fusion Program*, National Academy Press, Washington, D.C., 1989.

[5] President's Committee of Advisors on Science and Technology, The U.S. Program of Fusion Research and Development, Washington, D.C., July 11, 1995.

[6] U.S. Department of Energy, *Realizing the Promise of Fusion Energy: Final Report of the Task Force on Fusion Energy*, Secretary of Energy Advisory Board, Washington, D.C., August 9, 1999.

[7] NRC, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, Washington, D.C., 2004.

[8] NRC, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, Washington, D.C., 2009.

partnership brings to large multi-year endeavors at the frontier. Based on this review, the committee concludes that the United States benefits from partnership in ITER as the primary experimental burning plasma component within its own long-term strategic plan for fusion energy. On the other hand, a decision by the United States to withdraw from the ITER project would require a new approach to study a burning plasma. Because there is currently no mature burning plasma experiment as an alternative to ITER, the design, construction, and licensing of such an alternative to ITER would require significant development by the U.S. program, as well as a new approach to avoid isolation from the international fusion energy research effort.

The committee's final report will provide greater detail and analysis of the options for a long-term strategic plan for a national program of burning plasma science and technology research, including developing various supporting capabilities and participating in international activities. Strategic guidance for scenarios where the United States both is and is not a participant in ITER will be described.

Work for the final report is at an early stage. Nevertheless, based on the input received by the committee and the committee's assessments, if the United States seeks to continue its pursuit for abundant fusion power, the development of a national strategic plan for fusion energy that spans several decades is necessary. Therefore, the committee makes the following final assessment that will guide the strategies for both scenarios in the final report.

Assessment 7: If the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy.

In the development of the final report, the committee views the following elements as important to its guidance on a long-term strategic plan:

- Continued progress towards the construction and operation of a burning plasma experiment leading to the study of burning plasma,
- Research beyond what is done in a burning plasma experiment to improve and fully enable commercial fusion power,
- Innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and
- A mission for fusion energy research that engages the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

6

Toward Completion of the Final Report

Having completed its assessment of the status and importance of U.S. burning plasma research, the committee is now carrying out the detailed analyses of the many elements required to guide the nation's long-term strategic plan for fusion energy development. These analyses will be informed by input from the second community workshop on strategic directions for U.S. magnetic fusion research to be held at the University of Texas, Austin, December 11-15, 2017, and by several site visits. Additionally, a subcommittee of the Fusion Energy Sciences Advisory Committee (FESAC) to the U.S. Department of Energy Office of Science is expected to complete its report shortly identifying "the most promising transformative enabling capabilities for the United States to pursue that could promote efficient advance toward fusion energy." This new FESAC report will also inform U.S. strategies to improve the fusion power system. The committee anticipates that its final report will present strategies that incorporate continued progress toward a burning plasma experiment, include a major focus on innovation, include provisions for regular review in order to accommodate scientific and technological breakthroughs, and be built upon recent advances in burning plasma science, fusion nuclear science, and the international effort. To the extent possible, the final report will include considerations of the health of fusion research sectors within the United States, the role of international collaboration in the pursuit of national fusion energy goals, the capability and prospects of private-sector ventures to advance fusion energy concepts and technologies, the impact of science and technology innovations, and the design of research strategies that may shorten the time and reduce the cost required to develop commercial fusion energy.

Appendixes

A

What Is Magnetic Fusion?

While it has long been known that it is nuclear fusion that makes the Sun shine, the first concerted attempts to harness fusion power on Earth began in the 1950s, first in secret but collaboratively among many nations by 1958. These first efforts, and the fusion research described in this interim report, employed strong magnetic fields to confine the hot gases that produce fusion power. By the 1960s, the invention of the laser led to a different approach in which lasers quickly heat a tiny quantity of fuel that explodes as it burns.[1] This report deals only with magnetic fusion, which has had the best performance to date, leading to governmental discussions in the 1990s on how to advance magnetic fusion energy research as a world-wide endeavor—what is now the International Thermonuclear Experimental Reactor (ITER) project. Several books describe this history.[2,3,4]

A magnetic fusion reactor can be thought of as a miniature Sun confined inside a vessel that can be highly evacuated. A strong magnetic field confines the high-pressure plasma and limits contact between the surrounding vessel and the high-temperature plasma undergoing fusion reactions. The first fuel will probably be a mixture of deuterium (D), a form of hydrogen in all water, and another form of hydrogen called tritium (T) that would be manufactured inside the reactor. The energy potential in the tiny amount of deuterium in a gallon of water is equivalent to 300 gallons of gasoline. It is this abundance of fusion fuel, together with environmental advantages, that has inspired governments to support fusion research over many decades. D-T fuel produces harmless helium, together with neutrons that can make the reactor vessel radioactive, but with much less chance for danger to the public than fission reactors, according to studies reported in Chapter 15 of *The Fusion Quest*. This interim report discusses only fusion using D-T fuel, which is the focus of the world-wide research program. Magnetic fusion energy using either deuterium (D-D) or deuterium and helium-3 (D-^{3}He) fuel is more challenging due to requirements for higher temperature, reduced impurity concentration, and improved confinement.[5]

The challenge has been that producing fusion on Earth requires temperatures even hotter than stars and in the range between 100 and 200 million degrees. Gases this hot become ionized, consisting of a "plasma" of free ions and electrons, like the gases conducting electricity in a neon sign but requiring 10,000 times higher temperature. Magnetic fields are needed to confine hot, high-pressure plasmas by way of electric currents inside the ionized plasma. Many arrangements of magnets to confine a hot plasma have been tested. The most successful, and the one employed in ITER, is the tokamak configuration, originally developed in Russia and further explored and improved upon by research in the United States and elsewhere.

The tokamak is a descendant of the linear "pinch" known since the 1930s. In a pinch, a current flowing through a plasma column confines itself by its own magnetic fields produced by the current. Bending the current column into a circle prevents leakage out the ends, and doing this inside a "toroidal" or doughnut-shaped vessel keeps the air out. Coils above and below the toroidal vessel provide the magnetic force that bends the column into a

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[1] For more information on inertial fusion energy, see National Research Council, *An Assessment of the Prospects for Inertial Fusion Energy*, The National Academies Press, Washington, D.C., 2013.

[2] J.L. Bromberg, *Fusion*, MIT Press, Cambridge, Mass., 1982.

[3] T.A. Heppenheimer, *The Man-Made Sun*, Little-Brown, Boston, Mass., 1984.

[4] T.K. Fowler, *The Fusion Quest*, Johns Hopkins Press, Baltimore, Md., 1997.

[5] P.E. Stott, The feasibility of using D–3He and D–D fusion fuels, *Plasma Phys Contr F* 47:1305, 2005.

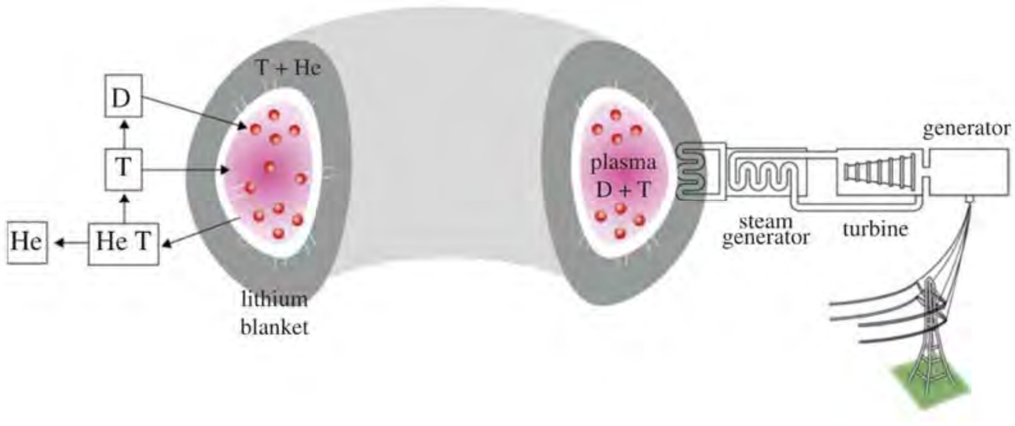

FIGURE A.1 A schematic of a magnetic fusion power plant showing (not to scale) the three parts: a hot burning plasma undergoing fusion reactions, a lithium "blanket" to capture fusion neutrons, and a heat-exchanger system with a turbine-driven electrical generator. SOURCE: C.L. Smith and S. Cowley, The path to fusion power, *Phil. Trans. R. Soc. A* 368:1091-1108, 2010.

circle. Other "toroidal field coils" wound on the vessel itself add a stabilizing twist to magnetic field lines inside the column. Thus, the tokamak has three sources of magnetic field: the pinch current that mainly confines the pressure; the "poloidal" coils that bend plasma current into a circle; and the strong "toroidal field coils" that twist the current into a highly stable confined plasma.

Fusion performance is measured by the pressure of the plasma, P, and the timescale for plasma energy escape, τ_E. The fusion power density produced from the fusion of deuterium and tritium (D-T) is equal to 0.08 P^2 megawatts per cubic meter (MW m^{-3}) when P is expressed in atmospheres. The record volume-averaged plasma pressure for magnetic fusion is 2.0 atmospheres and was set in October 2016 in the Alcator C-Mod device at the Massachusetts Institute of Technology. The plasma pressure expected in ITER is 2.6 atmospheres resulting in a peak fusion power density exceeding 0.5 MW m^{-3}. Commercial fusion energy systems would need to have plasma pressures between 3 and 8 atmospheres. The energy escape time, τ_E, determines whether or not the plasma is self-sustaining or whether external power must be injected to keep the plasma hot and at high pressure. ITER is designed to produce $\tau_E \sim 3.7$ seconds, and the product of the average pressure and τ_E is $P\tau_E \sim 10$ atm·sec. If the electron and ion pressures of the plasma are equal, the plasma becomes a "burning plasma" when the product $P\tau_E$ is greater than about 8 atm·sec. This is when the energetic alpha particles generated from fusion reactions in the plasma are able to balance the energy escaping from the plasma. The highest previous levels of plasma confinement product were achieved in tokamak experiments conducted in the 1990s: The Tokamak Fusion Test Reactor[6] achieved 0.3 atm·sec, the Joint European Tours[7] reached 0.7 atm·sec, JT-60[8] reached 0.65, and DIII-D reached a confinement parameter of $P\tau_E \sim 0.5$ atm·sec.[9]

Practical problems include how to get heat out of this circular device, how to prevent neutron damage to the magnet coils, and how to respond if, despite all, the strong current ring tries to short-circuit to the wall (called a "disruption"). What makes it worth dealing with these difficult issues is the remarkable fact that plasmas inside tokamaks can adjust themselves to reduce leakage of heat across the magnetic field. This "H-mode," or "high-

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[6] Hawryluk et al., Results from deuterium-tritium tokamak confinement experiments, *Rev. Mod. Phys.* 70:537, 1998.

[7] Keilhacker et al., High fusion performance from deuterium-tritium plasmas in JET, *Nuc Fusion* 39:209, 1999.

[8] H. Kishimoto et al., Advanced tokamak research on JT-60, *Nuc Fusion* 45:986, 2005.

[9] Lazarus et al., Higher fusion power gain with profile control in DIII-D tokamak plasmas, *Nuc Fusion* 37:7-12, 1997.

confinement mode," of tokamak operation, was discovered experimentally in the 1980s[10,11] and has been widely reproduced even as essential aspects of it remain enigmatic. ITER's baseline operating scenario is an H-mode plasma. Critical research efforts in the U.S. and abroad are focused both on ensuring that the ITER plasmas will attain and maintain H-mode performance and on developing alternative operating scenarios for ITER, which do not rely upon uncertain H-mode physics to attain the energy confinement that is required to create a burning plasma.

Whether a tokamak in the image of ITER will be the best path to a commercial reactor is much less certain, hence the need for continuing innovation to explore other paths. One such path is the stellerator being pursued in Germany and Japan. The stellarator is also a toroidal magnetic system but one not requiring the pinch current—nor the associated cost of maintaining it—as in tokamak reactors.

In addition to toroidal magnet configurations, a number of linear magnet configurations have been studied, all of which employ external power to create a closed magnetic field configuration of the plasma inside the linear magnets. Additionally, the tandem mirror configuration uses neutral beam injection and electron cyclotron resonance heating to modify electrostatic potentials and reduce plasma leakage out the ends. The only linear device large enough to compete with tokamak performance was the superconducting Mirror Fusion Test Facility that completed construction at the Lawrence Livermore National Laboratory in February 1986, only to be shut down before operating because of declining magnetic fusion budgets.

Whatever the final magnet shape, the fact that magnets might confine a plasma producing fusion energy on Earth completes a long journey, beginning with Michael Faraday's invention of the magnetic dynamo in 1831 and ending with Einstein's discovery that mass becomes energy, very soon leading to speculations about nuclear fusion long before fission was discovered. It was Faraday's discovery that prompted Maxwell to create the theory of light that eventually posed the puzzle that led to Einstein's $E = mc^2$.

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[10] Wagner et al., Regime of improved confinement and high beta in neutral-beam-heated divertor discharges of the ASDEX Tokamak, *Phys Rev Lett* 49:1408, 1982.

[11] Wagner et al., Development of an edge transport barrier at the H-mode transition of ASDEX, *Phys Rev Lett* 53:1453, 1984.

B

Statement of Task

A committee of the National Academies of Sciences, Engineering, and Medicine will be formed to study the state and potential of magnetic confinement-based fusion research in the United States and provide guidance on a long-term strategy for the field. The study will focus on research that supports understanding the magnetically confined burning plasma state but will take a broad view beyond plasma confinement science, and as such consider capabilities such as simulation and materials. Specifically, the committee will prepare an interim report that will:

3. Describe and assess the current status of U.S. research that supports burning plasma science, including current and planned participation in international activities, and describe international research activities broadly.
4. Assess the importance of U.S. burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

The committee will also prepare a final report, building on the interim report, which will:

3. Consider the scientific and engineering challenges and opportunities associated with advancing magnetic confinement fusion as an energy source, including the scientific and technical developments since the 2004 NAS[1] study on burning plasma research.
4. In two separate scenarios in which, after 2018, (1) the United States is a partner in ITER, and (2) the United States is not a partner in ITER: provide guidance on a long-term strategic plan (covering the next several decades) for a national program of burning plasma science and technology research which includes supporting capabilities and which may include participation in international activities, given the U.S. strategic interest in realizing economical fusion energy in the long term.

In doing the above, the committee will consider the priorities for the next ten years developed by the community and FES that were recently reported to Congress. The committee will also consider the current level of participation by U.S. scientists in international activities as well as what role international collaboration should play over the next 20 years. The committee will also consider the health of the domestic fusion research sectors (universities, national laboratories, and industry). Elements of any strategic plan for U.S. burning plasma research should ensure that the United States maintains a leadership role in this field. The committee may assume that economical fusion energy within the next several decades is a U.S. strategic interest. The committee may take into account how unanticipated events or innovations may necessitate mid-course re-directions. The committee will use the prior work of the Academies as well as that of FESAC and the domestic and foreign communities in its deliberations. The committee is not to compare fusion as an energy source against other current or potential energy sources. The committee will consider the budget implications of its guidance but will not make recommendations about the budget for burning plasma research itself. The committee will only consider magnetically confined burning plasma research as within its purview. The committee may make recommendations or offer comments on organizational structure and program balance, with accompanying supporting discussion of the evidentiary bases, as appropriate.

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before July 1.

C

Agendas from Committee Meetings

MEETING 1: JUNE 5-6, 2017

Keck Center of the National Academies
Washington, D.C

June 5, 2017

CLOSED SESSION

8:00 a.m.	Breakfast
9:00	Discussion
12:00 p.m.	Lunch
1:00	Discussion

OPEN SESSION

1:45	Reconvene
2:00	Perspective from DOE Fusion Energy Sciences, Ed Synakowski, DOE FES
3:00	Break
3:15	Perspectives from Capitol Hill, Adam Rosenberg and Emily Domenech, House Science, Space, and Technology
4:00	Perspectives from the U.S. Burning Plasma Organization, Chuck Greenfield, General Atomics, and Amanda Hubbard, MIT
5:00	Open public comments
5:30	Break

CLOSED SESSION

6:30	Committee dinner
8:30	Adjourn for the day

June 6, 2017

CLOSED SESSION

This day is held entirely in closed session.

MEETING 2: AUGUST 29-31, 2017

Beckman Center of the National Academies
Irvine, California

August 29, 2017

CLOSED SESSION

8:00 a.m.	Breakfast
9:00	Committee discussion

OPEN SESSION

9:30	Perspectives from the U.S. ITER Project, Ned Sauthoff, Oak Ridge National Laboratory Perspectives from the ITER Organization, Bernard Bigot, Director General
10:30	Break
11:00	Perspective on Fusion Energy Strategy, Stewart Prager, Princeton University
12:00 p.m.	Lunch
1:00	Perspective on Fusion Energy Strategy, Tony Taylor, General Atomics
2:00	Perspectives from University Fusion Associates, David Maurer, Auburn University
3:00	Break
3:30	Perspectives from the Virtual Laboratory for Technology, Phil Ferguson, Oak Ridge National Lab
4:30	Public comments

CLOSED SESSION

5:00	Discussion

OPEN SESSION

6:30	Dinner
8:30	Adjourn for the day

August 30, 2017

CLOSED SESSION

8:30 a.m.	Committee discussion
6:00 p.m.	Adjourn for the day

August 31, 2017

CLOSED SESSION

8:30 a.m.	Committee discussion
2:00 p.m.	Adjourn

D

Previous Studies of Magnetic Fusion Energy and Strategies for Fusion Energy Development Consulted by the Committee, 1984-2017

NRC (National Research Council). 1984. *Cooperation and Competition on the Path to Fusion Energy: A Report.* National Academy Press, Washington, D.C.

DOE (U.S. Department of Energy). 1985. *Magnetic Fusion Program Plan.* DOE/ER-0214. Washington, D.C. February.

DOE Energy Research Advisory Board. 1986. *Report of the Technical Panel on Magnetic Fusion*. Washington, D.C. November.

NRC. 1989. *Pacing the U.S. Magnetic Fusion Program*. National Academy Press, Washington, D.C.

DOE FEAC (Fusion Energy Advisory Committee). 1990. *Final Report*. Washington, D.C. September.

DOE FEAC. 1992. *Report on Program Strategy for U.S. Magnetic Fusion Energy Research*. DOE\ER-0572T. Washington, D.C. September.

PCAST (President's Committee of Advisors on Science and Technology). 1995. *The U.S. Program of Fusion Research and Development*. Washington, D.C. July 11.

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Biographies of Committee Members

MICHAEL MAUEL, *Co-Chair*, is a professor of applied physics at Columbia University. He received his B.S., M.S., and Sc.D. at MIT. While at MIT, he was awarded the Fortesque Fellowship from the IEEE and the Ernst A. Guillemin Thesis Award from MIT. Before joining Columbia in 1985, Dr. Mauel conducted post-doctoral research at MIT and conducted high-power electron cyclotron heating experiments at the Tara Tandem Mirror. His fields of interest include advanced tokamak operating regimes, feedback techniques to control tokamak instabilities, nonlinear turbulent transport in magnetized plasma including energetic particle modes, and the relationship between laboratory and space plasma physics. In 1995, he was elected a fellow for the American Physical Society. From 2000-2006 he was chair of the Department of Applied Physics and Applied Mathematics at Columbia. In 2006, he was a Jefferson Science Fellow for the U.S. Department of State. Dr. Mauel has served as a member of several committees in the American Physical Society and served as chair of the APS Division of Plasma Physics from 2002-2003. He was president of the University Fusion Association from 1997-1998, co-chair of the 1999 Fusion Summer Study in Snowmass, chair of the U.S. ITER Forum in 2003, chair of the U.S. Burning Plasma Council from 2010-2013, and chair of the National Academies Plasma Science Committee from 2012-2015. He served on several Fusion Energy Sciences Advisory Committee (FESAC) activities, including FESAC Office of Fusion Energy Committee of Visitors (2003-2004), FESAC Fusion Major Facilities Panel (2012-2013), FESAC Fusion Priorities Panel (2003-2004 and 2012-2013). He also served as chair of the physics advisory committees for the National Spherical Tokamak Experiment (NSTX) at the Princeton Plasma Physics Laboratory and the Alcator C-Mod experiment at MIT. Dr. Mauel received the Rose Award for Excellence in Fusion Engineering in 2000, the Teacher of the Year award from Columbia University's School of Engineering and Applied Science, and Certificates of Appreciation from the U.S. Department of Energy (1989) and the U.S. Department of State (2007). Since 2016, Dr. Mauel serves as editor-in-chief of Physics of Plasmas.

MELVYN SHOCHET [NAS], *Co-Chair*, is Kersten Distinguished Service Professor of Physics at the University of Chicago. Before joining the Enrico Fermi Institute at the University of Chicago in 1972, he received his PhD from Princeton University and his B.A. from the University of Pennsylvania. His research involves interactions between elementary particles at the highest manmade energies. He is a founding member of the Collider Detector at Fermilab (CDF) collaboration and served as the collaboration’s spokesperson from 1988-1995, including the period when nature’s heaviest constituent, the top quark, was discovered. For the past 15 years, he has been a member of the ATLAS collaboration at CERN, which discovered the Higgs boson in 2012. He was a member of the HEPAP Particle Physics Project Prioritization Panel (P5), and from 2005-2011, he served as chair of HEPAP. He also served on the BPA’s Committee on Elementary Particle Physics from 1995-1998. He is a fellow of the American Physical Society, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and a member of the National Academy of Sciences.

CHRISTINA BACK is an experimental physicist with expertise in the study of radiation in high energy density plasmas, and the development of novel materials for fusion and fission. Currently, she is the Vice President of Nuclear Technologies and Materials at General Atomics and leads a group developing high-density uranium fuels and advanced fuel cladding materials. She received her B. S. in Physics from Yale in 1984 and earned her Ph.D. in plasma physics from the University of Florida in 1989. After a 2 year postdoc with the CNRS at the Ecole Polytechnique in France, she spent 13 years at Lawrence Livermore

National Laboratory in the Inertial Confinement Fusion and High Energy Density Science programs, specializing in radiation transport and spectroscopy. In 2005, she moved to General Atomics where she was worked on target production coordination, development of novel radiation sources, and development of new fuel materials for advanced nuclear reactor. She established a dedicated laboratory for research fabricating and characterizing new fission fuel prototypes, especially those for gas-cooled high temperature reactors. She has served on many American Physics Society (APS) committees and has been elected as a APS General Councillor. Other professional service includes serving on the National Research Council (NRC) Board of Physics and Astronomy Plasma Committee, and as member of the NRC committee to Review the Quality of Science and Engineering Research at the DOE's National Security Laboratories Phase II (2012). Dr. Back is a Fellow of the American Physical Society.

RICCARDO BETTI is a professor of physics and mechanical engineering and of physics and astronomy, director of the Fusion Science Center of Extreme States of Matter and Fast Ignition, and a scientist at the Laboratory for Laser Energetics at the University of Rochester. His primary expertise is in the theory of high-temperatures plasmas. Dr. Betti is a member of the interdisciplinary High Energy Density Plasma program at Rochester's Laboratory for Laser Energetics. Dr. Betti is a member of DOE's Fusion Energy Sciences Advisory Committee and was the vice chair of a recent DOE review of inertial fusion energy, as well as many other review panels. Dr. Betti is a fellow of the American Physical Society. He received his Ph.D. from MIT in 1992 in nuclear engineering.

IAN CHAPMAN is the CEO of the UK Atomic Energy Authority and Head of the CCFE. His primary research interests are in understanding and controlling macroscopic instabilities in fusion plasmas. Ian Chapman was previously the head of tokamak science and led the stability program within tokamak science. He has also held a number of international roles in fusion. He was a task force leader for JET from 2012 to 2014. He was appointed a member of the program advisory committee for US experiment NSTX-U in 2013. He has chaired international working groups for ITER and led work packages within the EU fusion program. He received his Ph.D. in Plasma Physics from the Imperial College and M.Sci. in Mathematics and Physics from University of Durham.

CARY FOREST is a professor in the Physics Department at the University of Wisconsin Madison. He obtained his Ph.D. in Astrophysical Science-Plasma Physics from Princeton University in 1992. His research interests focus on understanding how electrical currents and magnetic fields are generated in fusion plasmas and in turbulent flows of liquid metals, with applications to astrophysical and terrestrial plasmas, basic plasmas, and fusion science. He spent five years working at General Atomics as a scientist, where his work focused on studies of plasma resistivity, non-inductive current drive, rf heating of plasmas and MHD instabilities in tokamak plasmas. He has served as director of the NSF Physics Frontier Center for Magnetic Self-Organization. He served as chair of the APS Division of Plasma Physics. He is a fellow of the American Physical Society. He has served as chair of the National Academies' Plasma Science Committee (2003-2006) and as a member of the Committee to Review a Plan Prepared by the U.S. Burning Plasma Organization for U.S. Fusion Community Participation in the ITER Program.

T. KENNETH FOWLER [NAS] is Professor Emeritus in the Department of Nuclear Engineering, University of California, Berkeley. Dr. Fowler received his BE in electrical engineering from Vanderbilt University in 1953, MS in physics from Vanderbilt in 1955, and Ph. D. in theoretical physics from the University of Wisconsin, Madison, in 1957. Before joining the Berkeley faculty in 1988, he spent thirty years in fusion energy research at the Oak Ridge National Laboratory, at General Atomics, and finally at the Lawrence Livermore National Laboratory, where he served as an Associate Director of the Laboratory and head of magnetic fusion energy research from 1970 to 1987. During 1987-1988, he was U. S. Representative on the Working Group that initiated the International Thermonuclear Experimental Reactor now known as ITER and under construction in France. He has served on numerous governmental and academic committees and served as Chair of the Department of Nuclear Engineering at Berkeley from 1988 to 1994. He was elected to the National Academy of Sciences in 1987. He is also a fellow of the California Council on Science and Technology that advises the Governor and Legislature on science important to the State. His honors include the Distinguished Service Citation from the University of Wisconsin in 1981 and the Berkeley Citation in 1995.

JEFFREY P. FREIDBERG is an emeritus professor of nuclear science and engineering at the Massachusetts Institute of Technology, and a senior researcher at NYU's Courant Institute of Mathematical Sciences. Previously he was the head of the Nuclear Science and Engineering Department at Massachusetts Institute of Technology. He also formerly served as the Director of MIT Plasma Science and Fusion Center. He earned his B.S., M.S. and Ph.D. degrees from Polytechnic Institute of Brooklyn (now New York University Tandon School of Engineering).

RONALD M. GILGENBACH is Chihiro Kikuchi Collegiate Professor in the Nuclear Engineering and Radiological Sciences Department at the University of Michigan. He is also a past associate editor of the journal Physics of Plasmas. In the 1970's he was a member of the technical staff at Bell Labs, performed gyrotron research at the Naval Research Lab (NRL), and electron cyclotron heating experiments on the ISX-B tokamak at Oak Ridge National Lab. He has collaborated in research with scientists at Air Force Research Lab, Sandia National Labs, NASA Glenn, Northrop-Grumman, L-3 Communications, General Motors Research Labs, Los Alamos National Lab, Fermilab, Naval Research Lab and Institute of High Current Electronics (Russia). He earned his Ph.D. in Electrical Engineering from Columbia University and M.S. and B.S. at the University of Wisconsin.

WILLIAM HEIDBRINK is a professor of experimental plasma physics at the University of California in Irvine. After working as a staff member on the TFTR tokamak (Princeton) and the DIII-D tokamak (General Atomics), he joined the UCI Physics Department in 1988. Professor Heidbrink studies high energy “fast” ions in magnetic fusion experiments. Instabilities that are driven unstable by the free energy in the fast-ion population are a major area of study. Other important topics include diagnostic development and measurements of fast-ion confinement. The research is conducted on two facilities. The DIII-D tokamak in San Diego is the leading magnetic fusion facility in the USA. Professor Heidbrink earned his B.A. degree from the University of California, San Diego and Ph.D. from Princeton University.

MARK HERRMANN i is the director of the National Ignition Facility (NIF), the world’s largest laser, at Lawrence Livermore National Laboratory (LLNL). NIF is a key experimental facility for the science-based Stockpile Stewardship Program. Dr. Herrmann spent 9 years at Sandia National Laboratories, where he studied the use of large magnetic fields generated by the Z facility to create and control high energy density matter. While at Sandia, he held a number of positions, including Director of the Pulsed Power Sciences Center. He began his career as a physicist at LLNL, where his research focused on inertial confinement fusion and high energy density science. He has been awarded a Presidential Early Career Award for Scientists and Engineers, the American Physical Society Award for Outstanding Doctoral Dissertation in Plasma Physics, and the Fusion Power Associates Excellence in Fusion Engineering Award. Mark is a fellow of the American Physical Society. He received his undergraduate degrees from Washington University in St. Louis, and his Ph.D. from the Program in Plasma Physics at Princeton University.

FRANK JENKO is a professor at the University of Texas at Austin and Director at the Max Planck Institute for Plasma Physics. He has been serving as professor in the Department of Physics & Astronomy and Director of the Plasma Science and Technology Institute (PSTI) at the University of California, Los Angeles (UCLA), as a member of the editorial boards of Computer Physics Communications, Journal of Plasma Physics, and New Journal of Physics, as a co-director of the International Helmholtz Graduate

School for Plasma Physics, and as a member of the steering committee of the Max-Planck/Princeton Center for Plasma Physics. He co-pioneered the development and application of grid-based numerical techniques for the investigation of kinetic turbulence in magnetized plasmas. Since then, his computer simulation code GENE has been playing a key role for analyzing both laboratory and natural plasmas, standing at the forefront of high-performance computing. Frank Jenko obtained his Ph.D. in physics from the *Technische Universität München* (TUM).

STANLEY KAYE is the principle research physicist and Deputy Director of Research on NSTX-U at the U.S Department of Energy's Plasma Physics Laboratory in Princeton University. He was recently named a Fellow by the American Physical Society (APS). He is considered a pioneering investigator of the characteristics of strongly heated plasmas confined by magnetic fields. Kaye received a Bachelor's degree in physics and math from Hamilton College in Clinton, New York, a Master's degree in geophysics and space physics from the University of Washington in Seattle, and a Ph.D. in space plasma physics from the University of California at Los Angeles.

MITSURU KIKUCHI is a supreme researcher at the Naka Fusion Institute, Fusion Research and Development Directorate, Japan Atomic Energy Agency. He joined JAEA in 1981 as a research associate. He has held visiting and guest professorships at Osaka University (Japan), Southwestern Institute of Physics (China), the Modern Physics Institute at Fudan University (China), and the Chinese Academy of Sciences. He has served as chairman of the Board of Editors of Nuclear Fusion. He is chair of the Division of Plasma Physics of the Association of Asia Pacific Physical Societies. He received his Doctor of Philosophy in Engineering from the University of Tokyo in 1981 at Japan Atomic Energy Agency.

SUSANA REYES is a nuclear engineer at Berkeley Lab with over 17 years of experience in international fusion projects. Until recently, she lead LLNL's fusion energy science efforts for safety and tritium research, as well as supporting the National Ignition Facility (NIF) Directorate in various Project Engineering and Strategic Planning activities. Dr. Reyes earned an M.Sci. in Power Engineering from the Polytechnic University of Madrid in 1998, and a Ph.D. in Nuclear Engineering from the UNED University in Madrid in 2001. Dr. Reyes joined LLNL's Fusion Energy Program in 1999 to work on the safety analysis of inertial fusion energy power plant designs. Since then, she has participated in the design, construction, and operation of a variety of fusion research projects, including the NIF in LLNL, and the ITER Organization in Cadarache (France), where she supported the project through the coordination of safety analyses and associated documentation in preparation for ITER licensing. Her current interests are focused on the safety and environmental aspects of fusion and the fuel cycle challenges for future fusion power plants. Dr. Reyes is the recipient of the 2012 American Nuclear Society (ANS) Mary Jane Oestmann Professional Women's Achievement Award, and the 2015 Fusion Power Associates Excellence 9 in Fusion Engineering Award, for her contributions to the safety and environmental aspects of both magnetic fusion energy (MFE) and inertial fusion energy (IFE) facilities. She recently served as chair of the American Nuclear Society's Fusion Energy Division.

HON. C. PAUL ROBINSON [NAE] is the vice-chairman of the Board of Directors of ARC. He was the ambassador to Russia under President Reagan. He spent most of his career at Los Alamos National Laboratory and Sandia National Laboratories, becoming President of Sandia Corporation in 1995. Dr. Robinson was elected to the National Academy of Engineering in 1998 and serves on the Committee on Membership. He received the Outstanding Public Service Medal from the Joint Chiefs of Staff, the Smyth Nuclear Statesman Award from the American Nuclear Society, the American Physical Society Pake Prize, the New Mexico Governor's Distinguished Citizen Award, and the Department of Energy Secretary's Gold Award. He has also served as a trustee of the Kazakhstan Nonproliferation Institute. Dr. Robinson earned a B.S. in Physics from Christian Brothers College and a Ph.D. in Physics from Florida State University, and received an honorary doctorate from Christian Brothers University.

PHIL SNYDER is the director of the Theory and Computational Science group for General Atomics' Energy And Advanced Concepts Group. He joined the General Atomics Theory and Computational Science Division in 1999, and became manager of the Turbulence and Transport group in 2010. His recent research has focused on the edge region of fusion plasmas, particularly the physics of the edge transport barrier ("pedestal") and edge localized modes in tokamaks. Dr. Snyder has served as chair of the Sherwood Executive Committee and the Edge Coordinating Committee, and is currently Principal Investigator of the Edge Simulation Laboratory project. He is a fellow of the APS (2010) and a recipient of the Rosenbluth Award for Fusion Theory (2004). Dr. Philip Snyder studied computational physics at Yale University, receiving his B.S. degree and then earned his Ph.D. in Plasma Physics from Princeton University.

AMY WENDT is a professor of Electrical and Computer Engineering at UW-Madison, where she has been a faculty member since 1990. Her research focus is ionized gas discharges for technological applications. Understanding the behavior of low-temperature plasmas, how they interact with materials substrates and implications for process and system design are the primary goals of her research. Her research group conducts experimental studies with activities including diagnostic development, plasma source design and process development. She is the co-Director of the Women in Science and Engineering Leadership Institute at UW-Madison, and received the 2015 College of Engineering Equity and Diversity Award. She served on the NRC Plasma Science Committee from 2007 to 2014, the Fusion Energy Sciences Advisory Committee (FESAC) from 2017 to 2020 and as chair of the Gaseous Electronics Conference Executive Committee from 2012 to 2014. Professor Wendt received MS and Ph.D. degrees in Electrical Engineering and Computer Science from UC Berkeley and a B.S. in Engineering from Caltech.

BRIAN D. WIRTH is a professor and Governor's Chair of Computational Nuclear Engineering in the Department of Nuclear Engineering at the University of Tennessee, Knoxville, which he joined in July 2010. Dr. Wirth spent four years in the High Performance Computational Materials Science Group at Lawrence Livermore National Laboratory, where he lead efforts to investigate the microstructural stability of structural materials in nuclear environments. In 2002 he joined the faculty at the University of California, Berkeley as an Assistant Professor of Nuclear Engineering and was promoted to Associate Professor in 2006. He has received a number of awards, including the 2007 Fusion Power Associates David J. Rose Excellence in Fusion Engineering Award and the 2003 Presidential Early Career Award for Scientists and Engineers (PECASE). Brian received a BS in nuclear engineering from the Georgia Institute of Technology and a PhD in mechanical engineering from the University of California, Santa Barbara.

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Glossary and Acronyms

ANS	American Nuclear Society
APS	American Physical Society
ARIES	
BPA	Board on Physics and Astronomy
BSCCO	Bismuth Strontium Calcium Copper Oxide
CANDU	Canada Deuterium Uranium
CD	Current Drive
CEA	French Alternative Energies and Atomic Energy Commission
CFETR	China Fusion Energy Test Reactor
CFS	Commonwealth Fusion Systems
CTH	
DEMO	Demonstration Power Plant
DOE	U.S. Department of Energy
DONES	DEMO-Oriented Neutron Source
ECCD	Electron Cyclotron Current Drive
ECFS	Early Career Fusion Scientists
EFDA	European Fusion Development Agreement
EHO	Edge Harmonic Oscillation
ELM	Edge Localized Modes
EP	Energetic Particle
EU	European Union
FACA	Federal Advisory Committee Act
FES	Office of Fusion Energy Sciences
FESAC	Fusion Energy Sciences Advisory Committee
FINESSE	Fusion Integral Nuclear Experiments Strategy Study Effort
FPCC	Fusion Power Coordinating Committee
FRC	Field-Reversed Configuration
FSNF	Fusion Nuclear Science Facility
FW	Fast Waves
FY	Fiscal Year
GAO	U.S. Government Accountability Office
GE	General Electric Company
GDC	General Dynamics Convair Division
GDT	Gas Dynamic Trap
HEPAP	High Energy Physics Advisory Panel
HIFR	High Flux Isotope Reactor
HSX	Helically Symmetric Experiment
HTS	High Temperature Superconductors
IEEE	Institute for Electrical and Electronics Engineers
IFMIF	International Fusion Materials Irradiation Facility
IO	International Organization

ITPA	International Tokamak Physics Activity
IRP	ITER Research Plan
INL	Idaho National Laboratory
ITER	International Thermonuclear Experimental Reactor
JET	
LCP	Large Coil Project
LCTF	Large Coil Test Facility
LH	Lower Hybrid
LHC	Large Hadron Collider
LHD	Large Helical Device
LM	Liquid Metal
LTC	Low Temperature Superconducting
LTS	Low-Critical-Temperature Superconductors
NB	Neutral Beams
MAST-U	
MaPLE	Magnetohydrodynamic PbLi Experiment
MELCOR	
MFR	U.S. Magnetic Fusion Research
MGI	Massive Gas Injection
MIT	Massachusetts Institute of Technology
MHD	Magnetohydrodynamic
NAS	U.S. National Academy of Sciences
NASEM	National Academies of Science, Engineering, and Medicine
NERSC	National Energy Research Supercomputer Center
NBCD	
NIF	National Ignition Facility
NIFS	National Institute for Fusion Science
NRC	U.S. National Research Council
NSTX	National Spherical Torus Experiment
NTM	Neoclassical Tearing Modes
OFES	Office of Fusion Energy Sciences
OPG	Ontario Power Generation
ORNL	Oak Ridge National Laboratory
PFC	Plasma Facing Components
PISCES	Plasma Surface Interaction Experimental Facility
PMI	Plasma-Material Interactions
PSI	Swiss Paul Scherrer Institute
QA	Quasi-Axisymmery
QH	Quasi-Helical-Symmetry
REBCO	Rare-Earth Barium Copper-Oxides
RF	Radio Frequency
RM	Remote Maintenance
ROK	Republic of Korea
SAS	Small-Angle Slot
SLM	Selective Laser Melting
SPI	Shattered Pellet Injection
STAR	Safety and Tritium Applied Research
STARLITE	
TBM	Test Blanket Module
TBR	Tritium Breeding Ratios

TEC	Transformative Enabling Capabilities
TFTR	Tokamak Fusion Test Reactor
TGAP	Tritium Gas Absorption Permeation
TMAP	Tritium Migration Analysis Program
TPE	Tritium Plasma Experiment
TCV	TCV is a medium size tokamak, *Tokamak à Configuration Variable*, (EPFL Lausanne, Switzerland, https://spc.epfl.ch/research_TCV_Tokamak)
UFA	University Fusion Association
USBPO	United States Burning Plasma Organization
VLT	Virtual Laboratory for Technology
VNS	Volume Neutron Source
WCM	Weakly Coherent Mode
WDM	Whole Device Modeling
WH	Westinghouse Electric Corporation