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

Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research

DETAILS

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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
Division on Engineering and Physical Sciences

A Consensus Study Report of
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

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[1] NAS, National Academy of Sciences.

Preface

In January 2003, President George W. Bush announced that the United States would begin negotiations to join the 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." In 2007, the United States became an ITER member after signing a binding international agreement with China, the European Union (EU), India, Japan, the Republic of Korea (ROK), 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 FY2016 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 FY2018. 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 United States 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 "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."

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.

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 (FESAC) 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 Blandford, Stanford University,
Richard Buttery, General Atomics,
James D. Callen, University of Wisconsin,
Steve Cowley, Corpus Christi College,
Robert Iotti, ARC Nuclear,
Johnathan Menard, Princeton University,
Ann White, Massachusetts Institute of Technology, and
Steven Zinkle, 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 Rieke, 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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APPENDIXES

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 seconds 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 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, 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 NRC Burning Plasma Committee 2004, 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*,[1] *Pacing the U.S. Magnetic Fusion Program*,[2] the 1995 Report PCAST Panel on U.S. Fusion R&D Programs,[3] and *Realizing the Promise of Fusion Energy*.[4] After considering various options for a burning plasma experiment, the 2004 NRC Burning Plasma Assessment Committee[5] 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 NRC's report *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*[6] 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 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.

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[1] National Research Council, *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, 1984.

[2] National Research Council, *Pacing the U.S. Magnetic Fusion Program*, National Academy Press, 1989.

[3] President's Committee of Advisors on Science and Technology, "The U.S. Program of Fusion Research and Development," July 11, 1995.

[4] Secretary of Energy Advisory Board, *Realizing the Promise of Fusion Energy: Final Report of the Task Force on Fusion Energy*, August 9, 1999.

[5] See *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[6] National Research Council, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, 2009.

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,[7] the focus and priority of the U.S. fusion energy sciences program changed. President George W. Bush announced[8] "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 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.[9] "A burning plasma experiment would address for the first time the scientific and technological questions that all energy-producing fusion schemes must face."[10] As explained in the 1999 Fusion Energy Sciences Advisory Committee (FESAC) report *Burning Plasma Physics*,[11] "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." 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.[12] The President's Committee of Advisors in Science and Technology (PCAST) report of the

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[7] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[8] George W. Bush: "Fact Sheet: ITER," January 30, 2003. Online by Gerhard Peters and John T. Woolley, The American Presidency Project. http://www.presidency.ucsb.edu/ws/?pid=80124.

[9] See, for example, *Final Report of the Fusion Policy Advisory Committee*, delivered to Energy Secretary Watkins, September, 1990.

[10] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[11] *Burning Plasma Physics*, FESAC Report, DOE/SC-0041, September 1999.

[12] For example, National Research Council, *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, 1984.

Fusion Review Panel[13] and the 1996 report of the Fusion Energy Advisory Council (FEAC), *Restructured Fusion Energy Sciences Program*,[14] recommended that the United States should "pursue fusion energy science and technology as a partner in the international effort." The report of the NRC Fusion Science Assessment Committee[15] recommended that "solid support should be developed within the broad scientific community" for U.S. participation in a burning plasma experiment, and the Secretary of Energy Advisory Board Task Force on Fusion Energy[16] urged "solid support for it throughout the political system."

These previous reports, the successful production of 11 MW fusion power in the Tokamak Fusion Test Reactor experiment[17] and 16 MW in JET,[18] 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.[19] 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 U.S. Department of Energy (DOE) *Twenty-Year Outlook*[20] listed ITER as the highest priority within the Office of Science.

Following decades of effort, including the International Tokamak Reactor project (1978–1987)[21] and the ITER Engineering Design Activity (1992–1998),[22] both facilitated through the 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.[23] 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,[24] ITER construction began in 2010 in Cadarache, France.[25] In 2012, by French Order, ITER became the first of a kind licensed basic nuclear fusion facility.[26]

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[13] *The U.S. Program of Fusion Energy Research and Development*, PCAST Fusion Review Panel (July, 1995).

[14] *A Restructured Fusion Energy Sciences Program*, FEAC Advisory Committee (January, 1996).

[15] *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, National Academies Press, (2001), http://www.nap.edu/catalog/9986.html.

[16] *Realizing the Promise of Fusion Energy*, Final Report of the SEAB Task Force on Fusion Energy (August, 1999).

[17] Hawryluk, et al., "Results from deuterium-tritium tokamak confinement experiments," *Rev. Mod. Phys*. 70, 537 (1998).

[18] Keilhacker et al., "High fusion performance from deuterium-tritium plasmas in JET," *Nuc Fusion* 39, 209 (1999).

[19] National Research Council, *Burning Plasma–Bringing a Star to Earth*, National Academy Press, 2004.

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

[21] See INTOR TEAM, *International Tokamak Reactor: Phase 2A*, Part III, IAEA, Vienna (1988).

[22] R. Aymar, "Present status and future prospect of the ITER project," *J Nucl Mater* 258, 56 (1998).

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

[24] R. Hawryluk, et al., "Principal physics developments evaluated in the ITER design review," *Nuclear Fusion* 49, 065012 (2009).

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

[26] Implementation at ITER of the French Order of 7 February 2012, concerning basic nuclear installations within the European Domestic Agency, P. Wouters et al. (2017) *Nucl. Fusion* 57 100401.

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.[27] These reports helped to motivate significant management improvements taken by the ITER Council,[28] which included the accelerated appointment of a new ITER Director General.

In March 2015, Dr. 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 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.[29]

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,[30] including completion of the first two of eighteen 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, CA) 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,[31] and all twenty-five milestones due by the end of second-quarter 2017 have been achieved.[32]

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

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[27] *FUSION ENERGY: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor*, U.S. GAO Report to Congress, GAO-14-499, June 2014.

[28] United States Department of Energy, *U.S. Participation in the ITER Project*, Report to Congress, May 2016.

[29] *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, U.S. DOE/OS/FES (January, 2017).

[30] "Perspectives from the US ITER Project," Ned R. Sauthoff, presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research (August 29, 2017).

[31] Report of the 20th Meeting of the ITER Council, 22 June 2017, https://www.iter.org/news/pressreleases.

[32] "Perspectives from the US ITER Project," Ned R. Sauthoff, presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research (August 29, 2017).

necessarily become the highest priority in the program."[33] 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[34] 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 2014, the U.S. ITER Project received about 40 percent of the U.S. fusion program budget.[35] 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 R&D 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."[36] The National Compact Stellarator Experiment under construction at the Princeton Plasma Physics Laboratory was 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."[37] 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.[38]

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:

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[33] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[34] National Research Council, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, 2009.

[35] Department of Energy FY2015 budget request.

[36] See "DOE Plans Termination of All Fusion Technology Efforts" Fusion Power Associated (FPN04-17 March 10, 2004), http://aries.pppl.gov/FPA/ARC04/fpn04-17.shtml.

[37] T. Feder, "U.S. narrows fusion research focus, joins German stellarator," *Phys. Today* (Sept. 2011) p. 30.

[38] Based on appropriated budgets reported in the DOE/FES annual budget requests to Congress for FY2003 and FY2017.

(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.[39] 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[40]: (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."[41] 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.[42] Similar national roadmaps leading to the demonstration of fusion power guide research in China[43] and Japan.[44]

Presently, the United States 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."[45]

The baseline cost and schedule for U.S. contributions to the ITER's first plasma subproject are now formalized.[46] 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 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 $100–125 million annually for more than 2 decades, and, "future budget

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[39] United States Department of Energy, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, December 2015.

[40] See DOE/FES annual budget requests to Congress for FY2015 through FY2017.

[41] United States Department of Energy, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, December 2015.

[42] *Fusion Electricity: A roadmap to the realization of fusion energy*, European Fusion Development Agreement (EFDA), November 2012.

[43] Wu, et al., "Identification of safety gaps for fusion demonstration reactors," *Nature Energy* 1, 16154 (2016).

[44] Yamada, et al., "Japanese endeavors to establish technological bases for DEMO," *Fusion Eng and Design* 109, pp. 1318-1325 (2016).

[45] United States Department of Energy, *U.S. Participation in the ITER Project*, Report to Congress, May 2016.

[46] *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, U.S. DOE/OS/FES (January, 2017).

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."[47]

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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[47] United States Department of Energy, *U.S. Participation in the ITER Project*, Report to Congress, May 2016.

2

The Committee's Information-Gathering Process

The assessments in this report are based on the following: [48]

- 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 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 through July 28, 2017;

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[48] See Appendix D for the source material used for the Committee's information-gathering process.

- Relevant review articles published in the scientific literature—for example, describing (1) scientific and technical achievements since the 2004 report of the NRC Burning Plasma Assessment Committee, (2) the magnetic fusion energy development path,[49] (3) the scientific opportunity afforded by study of a burning plasma experiment,[50,51] and (4) the plan of Director General Bernard Bigot to correct organizational problems and sustain ITER construction performance;[52] 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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[49] 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).

[50] J. Ongena, R. Koch, R. Wolf, and H. Zohm, "Magnetic-confinement fusion," *Nature Phys* 34, 398 (2016).

[51] 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).

[52] 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."[53] 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 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 burning plasma 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

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[53] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

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.[54,55]

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 have been extensively tested against experiments, resulting in significantly improved capability to predict fusion performance.[56] For illustration, these computational tools predicted new high-performance regimes that were subsequently observed in experiments of the U.S. fusion research program.[57] 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.[58] 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),[59] Enhanced Pedestal H-mode (EP-H-mode), or I-mode regime,[60] or actively controlled by applying resonant magnetic perturbations[61] (a technique pioneered in the United States), pellet injection, and position control.[62] The United States has also led the world in the development of techniques for understanding, as well as predicting, avoiding

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[54] Chen and Zonca, "Physics of Alfvén waves and energetic particles in burning plasmas," *Rev Mod Phys* 88, 015008 (2016).

[55] Gorelenkov, Pinches, Toi, "Energetic particle physics in fusion research in preparation for burning plasma experiments." *Nuc Fusion* 54, 125001 (2014).

[56] Kinsey, et al., "ITER predictions using the GYRO verified and experimentally validated trapped gyro-Landau fluid transport model," *Nuc Fusion* 51, 083001 (2011).

[57] 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).

[58] Buttery, et al., "DIII-D research to address key challenges for ITER and fusion energy," *Nuc Fusion* 55, 104017 (2015).

[59] 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).

[60] 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).

[61] Evans, et al., "RMP ELM suppression in DIII-D plasmas with ITER similar shapes and collisionalities," *Nuc Fusion* 48, 024002 (2008).

[62] 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).

and/or controlling disruptions of the plasma current—the latter by massive gas injection,[63] shattered pellets, and shell pellets.[64] 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.[65]

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[66] and into a divertor, where the plasma heat and particle flux can be nearly extinguished by interaction with recycling neutrals.[67] Additionally, because carbon-based first-wall materials must have low tritium retention,[68] important plasma-material processes such as erosion, tritium co-deposition, dust generation, and neutron-irradiation damage require evaluation in a burning plasma experiment.[69] 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.[70,71] 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.[72] Additionally, high fidelity integrated models,[73] 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.[74] The U.S.

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[63] Hollmann, et al., "Measurements of injected impurity assimilation during massive gas injection experiments in DIII-D," *Nuc Fusion* 48, 115007 (2008).

[64] Commaux, et al., "Demonstration of rapid shutdown using large shattered deuterium pellet injection in DIII-D," *Nuc Fusion* 50, 112001 (2010).

[65] Lehnen, et al., "Impact and mitigation of disruptions with the ITER-like wall in JET," *Nuc Fusion* 53, 093007 (2013).

[66] Goldston, "Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks," *Nuc Fusion* 52, 013009 (2012).

[67] Krasheninnikov, et al., "Edge and divertor plasma: detachment, stability, and plasma-wall interactions," *Nuc Fusion* 57, 102010 (2017).

[68] 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).

[69] Roth, et al. "Recent analysis of key plasma wall interactions issues for ITER," *J Nuc Materials* 390-91, pp. 1-9 (2009).

[70] Kugel, et al., "Evaporated lithium surface coatings in NSTX," *J. Nuc Materials* 390-91, pp. 1000-1004 (2009).

[71] Umansky, et al., "Attainment of a stable, fully detached plasma state in innovative divertor configurations," *Phys Plasmas* 24, 056112 (2017).

[72] Solomon, et al., "DIII-D research advancing the scientific basis for burning plasmas and fusion energy," *Nuc Fusion* 57, 102018 (2017).

[73] 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).

[74] Sips, et al., "Progress in preparing scenarios for operation of the International Thermonuclear Experimental Reactor," *Phys Plasmas* 22, 021804 (2015).

research program has led the world in the development of quiescent plasma scenarios not subject to damaging transient events[75] and the so-called "advanced inductive scenario,"[76] 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,[77] and compatible divertor concept.[78,79]

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.[80] 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.[81]

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 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.[82,83,84]

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[75] 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).

[76] Luce, et al., "Development of advanced inductive scenarios for ITER," *Nuc Fusion* 54, 013015 (2014).

[77] Evans, et al., "ELM suppression in helium plasmas with 3D magnetic fields," *Nuc Fusion* 57, 086016 (2017).

[78] Wenninger, et al., "Advances in the physics basis for the European DEMO design," *Nuc Fusion* 55, 063003 (2015).

[79] Ongena, et al., "Magnetic-confinement fusion," *Nat Phys* 34, 398 (2016).

[80] 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/).

[81] 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).

[82] Sawan and Abdou, "Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle," *Fusion Eng and Design* 81, pp. 1131-1144 (2006).

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.[85] A burning plasma experiment will be an integrated demonstration of the safety, reliability, and effectiveness of these technologies.[86]

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.[87] 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.[88] 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.[89,90,91]

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,[92] sustain plasma current,[93] modify temperature and current profiles, and control plasma instabilities.[94] 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 toroidal current. Sources are available for both

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[83] Giancarli, et al., "Overview of the ITER TBM Program," *Fusion Eng and Design* 87, 395 (2012).

[84] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[85] Girard, et al., "TER, safety and licensing," *Fusion Eng Des* 82, 506 (2007).

[86] Bornschein, et al., "Tritium management and safety issues in ITER and DEMO breeding blankets," *Fusion Eng Des* 88, 466 (2013).

[87] Zinkle and Snead, "Designing Radiation Resistance in Materials for Fusion Energy," *Annu. Rev. Mater. Res.* 44, 241 (2014).

[88] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[89] Raffray, et al., "High heat flux components-Readiness to proceed from near term fusion systems to power plants," *Fusion Eng and Design* 85, pp. 93-108 (2010).

[90] Zinkle and Snead, "Designing Radiation Resistance in Materials for Fusion Energy," *Annu. Rev. Mater. Res*. 44, 241 (2014).

[91] *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[92] Omori, et al., "Overview of the ITER EC H&CD system and its capabilities," *Fusion Eng and Design* 86, pp. 951-954 (2011).

[93] Cesario, et al., "Current drive at plasma densities required for thermonuclear reactors," *Nature Comm* 1, 55 (2010).

[94] Sauter, et al., "On the requirements to control neoclassical tearing modes in burning plasmas," *Plasma Phys Control Fusion* 52, 025002 (2010).

applications.[95] 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.[96]

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.[97] 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.[98,99] However, the costs and performance of these advanced superconductors will not be fully understood without experience at the industrial scale,[100] and new integrated scenarios for high-field fusion must be developed and tested.[101]

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,[102] high-field tokamak,[103] spherical tokamak, and stellarator.[104] The recent Advanced Reactor Innovation and Evaluation Study—Advanced and Conservative Tokamak tokamak studies[105] 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

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[95] Hill, et al., "DIII-D research towards resolving key issues for ITER and steady-state tokamaks," *Nuc Fusion* 53, 104001 (2013).

[96] Thumm, M., "Recent Advances in the Worldwide Fusion Gyrotron Development," *IEEE Trans Plasma Sci* 42, pp. 590-599 (2014).

[97] Mitchell and Devred, "The ITER magnet system: configuration and construction status," (in press) *Fusion Eng. Des.* (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.02.085.

[98] Fietz, et al., "Prospects of High Temperature Superconductors for fusion magnets and power applications," *Fusion Eng Des* 88, 440 (2013).

[99] 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).

[100] 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).

[101] Whyte, et al., "Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path," *J Fusion Energy* 35, 41 (2016).

[102] Chan, et al., "Physics Basis of a Fusion Development Facility Utilizing the Tokamak Approach," *Fusion Sci and Technology* 57, pp. 66-93 (2010).

[103] Whyte, et al., "Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path," *J Fusion Energy* 35, 41 (2016).

[104] Menard, et al., "Prospects for pilot plants based on the tokamak, spherical tokamak and stellarator," *Nuc Fusion* 51, 103014 (2011).

[105] C. E. Kessel, et al., The ARIES Advanced and Conservative Tokamak Power Plant Study, *Fusion Science and Technology* 67:1, 1-21, (2015), DOI: 10.13182/FST14-794.

which physics or engineering quantities have high leverage in improving reactor performance and economics.

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.*[106] 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.[107] Burning plasma physics also contributes to understanding important plasma processes like magnetic reconnection,[108] kinetic turbulent processes in magnetized plasma,[109] nonlinear wave-particle interactions and resonances,[110] and multi-scale phenomena that are also common to space and astrophysical plasma.[111] Materials research in support of burning plasma science contributes to better understanding of irradiated materials.[112,113] Additionally, fusion facilities can be used to advance fundamental and non-fusion plasma physics.[114]

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

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[106] *Applications of Fusion Energy Sciences Research: Scientific Discoveries and New Technologies Beyond Fusion*, FESAC Office of Science Department of Energy, (Sept 2015). https://science.energy.gov/~/media/fes/fesac/pdf/2015/2101507/FINAL_FES_NonFusionAppReport_090215.pdf.

[107] Ibid.

[108] Yamada, Kulsrud, and Ji, “Magnetic Reconnection,” *Rev. Mod. Phys*. 82, 603 (2010).

[109] Howes, “Kinetic Turbulence,” in *Magnetic Fields in Diffuse Media*, edited by Lazarian, de Gouveia Dal Pino, and Melioli (Springer Berlin Heidelberg, Berlin, Heidelberg, 2015), pp. 123–152.

[110] Breizman, “Nonlinear Consequences of Energetic Particle Instabilities,” *Fusion Sci and Tech*. 59**,** pp. 549-560 (2011).

[111] Burch, et al., “Magnetospheric Multiscale Overview and Science Objectives,” *Space Sci Rev* 199, pp. 5-21 (2016).

[112] Zinkle and Snead, “Designing Radiation Resistance in Materials for Fusion Energy,” *Annu. Rev. Mater. Res*. 44, 241 (2014).

[113] Bai, et al., “Efficient Annealing of Radiation Damage Near Grain Boundaries via Interstitial Emission,” *Science* 327, 1631 (2010).

[114] See, for example, the DIII-D Frontier Science Campaign, https://fusion.gat.com/global/diii-d/frontier.

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.[115] 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,[116] applied mathematics,[117] and computer science,[118] with wide visibility and impact.[119]

The substantial impacts of burning plasma research on science, technology, and engineering were identified in the 2004 NAS Burning Plasma Assessment Committee, 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[120]), which have medical and industrial processing applications.[121]

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[115] Schekochihin, et al., "Astrophysical Gyrokinetics: Kinetic and Fluid Turbulent Cascades in Magnetized Weakly Collisional Plasmas," *ApJS* 182, 310 (2009).

[116] Odette, Alinger, and Wirth, "Recent developments in irradiation-resistant steels," *Ann Rev Mat Res*. 38, pp. 471-503 (2008).

[117] Dongarra, Hittinger (Co-Chairs), et al., *Applied Mathematics Research for Exascale Computing*, 2014. Report of DOE Working Group on Exascale Mathematics, http://science.energy.gov/~/media/ascr/pdf/research/am/docs/EMWGreport.pdf.

[118] Batchelor, et al., "Simulation of fusion plasmas: Current status and future direction," *Plasma Sci and Techn* 9, 312 (2007).

[119] *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.

[120] 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).

[121] 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, 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 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[122] 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,[123,124,125] energetic particle physics,[126] and pedestal physics.[127] Many of the most widely

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[122] 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).

[123] Ku, Chang, 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).

[124] 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).

[125] 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).

[126] Fasoli, et al., "Physics of energetic ions," *Nuc Fusion* 47, pp. S264-S284 (2007).

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 integrated simulations for magnetic fusion energy sciences.[128] 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.[129] These same predictive tools have been employed to develop high-performance scenarios for ITER and other planned devices.[130] 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.[131]

Exascale computing platforms present great opportunities for computational physics.[132] The increased computing power should allow researchers to investigate new and previously inaccessible problems in burning plasma science.[133] 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[134] 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 FY2016, 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

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[127] Ferraro, Jardin, Snyder, "Ideal and resistive edge stability calculations with M3D-C-1," *Phys Plasmas* 17, 102508 (2010).

[128] *Integrated Simulations for Magnetic Fusion Energy Sciences*, Report from the DOE Workshop Held June 2-4, 2015.

[129] 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).

[130] 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).

[131] Xanthopoulos, et al., "Controlling Turbulence in Present and Future Stellarators," *Phys Rev Lett* 113, 155001 (2014).

[132] 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.

[133] *Integrated Simulations for Magnetic Fusion Energy Sciences*, Report from the DOE Workshop Held June 2-4, 2015.

[134] See https://www.exascaleproject.org/pppl-physicists-win-ecp-funding/.

Congressional Budget Request (pp. 137-138).[135] 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"[136] 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,[137] immediately following experiments that set the world's record for volume-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[138] 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[139] and by the 2014 FESAC Subcommittee on Strategic Planning.[140] 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.[141]

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.

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[135] See U.S. DOE Office of Science FY2016 Congressional Budget Request for Fusion Energy Sciences, (2015), p. 137-138.

[136] See https://science.energy.gov/fes/research/advanced-tokamak/.

[137] 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).

[138] See U.S. DOE Office of Science FY2016 Congressional Budget Request for Fusion Energy Sciences, (2015), p. 137-138.

[139] Fusion Energy Sciences Advisory Committee, "Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science," March 21, 2013.

[140] Fusion Energy Sciences Advisory Committee, "Report on Strategic Planning: Priorities Assessment and Budget Scenarios," December 2014.

[141] LaBombard, et al., "ADX: a high field, high power density, advanced divertor and RF tokamak," *Nuc Fusion* 55, 053020 (2015).

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),[142] KSTAR (Republic of Korea),[143] and Wendelstein 7-X (Germany).[144] 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[145] and additional amounts for personnel and materials during construction. The HL-2M tokamak is under construction at the Southwestern Institute of Physics[146] as an upgrade to the existing HL-2A[147] 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.[148] Non-U.S. proposals for new facilities include the superconducting Divertor Tokamak Test facility[149] 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[150] 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[151] and during the first fusion community workshop[152] 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

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[142] Wu, “An overview of the EAST project,” *Fusion Eng and Design* 82, 463 (2007).

[143] Oh, et al., “Commissioning and initial operation of KSTAR superconducting tokamak,” *Fusion Eng and Design* 84, 344 (2009).

[144] Bosch, et al., “Final integration, commissioning and start of the Wendelstein 7-X stellarator operation,” *Nuc Fusion* 57, 116015 (2017).

[145] See http://www.ipp.mpg.de/4010154/02_16.

[146] Liu, et al., “Assembly study for HL-2M tokamak,” *Fusion Eng Design* 96-97, pp. 298-301 (2015).

[147] Duan, et al., "Overview of recent HL-2A experiments," *Nuc Fusion* 57, 102013 (2017).

[148] Shirai, Barabaschi, 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).

[149] Crisantia, et al., “The Divertor Tokamak Test facility proposal: Physical requirements and reference design,” *Nuc Materials and Energy* 12, 1330 (2017).

[150] Song, et al., “Concept Design of CFETR Tokamak Machine,” *IEEE Trans Plasma Sci* 42, 503 (2014).

[151] For example, “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).

[152] 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).

universities, nine national laboratories, and one private company.[153] 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.[154]

Since the 2004 NRC Burning Plasma Assessment report, 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,[155] 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,[156,157] tritium fusion fuel cycle development,[158] pellet injection for fueling and disruption mitigation,[159] and the manufacture of the ITER central solenoid.[160] 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,[161] nanostructured[162] and oxide dispersed strengthened steels,[163] all aspects of SiC/SiC technology,[164] and new understanding of tungsten[165] and tungsten composites[166] 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

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[153] "Response to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research," Phil Ferguson, presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research (August 29, 2017). See also http://vlt.ornl.gov/.

[154] Baker, Charles C., "An overview of enabling technology research in the United States," *Fusion Engineering and Design* Volumes 61–62, November 2002, Pages 37-45.

[155] 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).

[156] Duckworth, et al., "Development and Demonstration of a Supercritical Helium-Cooled Cryogenic Viscous Compressor Prototype for the ITER Vacuum System," in *Adv Cryogenic Eng*, v. 57A and 57B, pp. 1234-1242 (2012).

[157] Perevezentsev, et al., "Study of Outgassing and Removal of Tritium from Metallic Construction Materials of ITER Vacuum Vessel Components," *Fusion Sci and Technology* 72, pp. 1-16, (2017).

[158] Klein, Poore, and Babineau, "Development of fusion fuel cycles: Large deviations from US defense program systems," *Fusion Eng Des* 1 (2015).

[159] Lyttle, et al.,"Tritium Challenges and Plans for ITER Pellet Fueling and Disruption Mitigation Systems," *Fusion Sci and Tech* 71, 251 (2017).

[160] Libeyre, P., Cormany, C., Dolgetta, N., et al., "Starting Manufacture of the ITER Central Solenoid," *IEEE Trans on Applied Superc* 26, 4203305 (2016).

[161] 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).

[162] Parish, et al., "Helium sequestration at nanoparticle-matrix interfaces in helium plus heavy ion irradiated nanostructured ferritic alloys," *J. Nuc. Materials* 482, 21 (2017).

[163] Zinkle, et al., "Development of next generation tempered and ODS reduced activation ferritic/martensitic steels for fusion energy applications," *Nuc Fusion* 57, 092005 (2017).

[164] Snead, et al., "Silicon carbide composites as fusion power reactor structural materials," *J Nuc Materials* 417, 330, (2011).

[165] Baldwin and Doerner, "Helium induced nanoscopic morphology on tungsten under fusion relevant plasma conditions," *Nuc Fusion* 48, 035001 (2008).

[166] Garrison, et al., "Irradiation effects in tungsten-copper laminate composite," *J Nuc Materials* 481, 134 (2016).

expected in fusion divertors. In the United States, linear plasma simulators include the PISCES facility at University of California, San Diego,[167] the Tritium Plasma Experiment at Idaho National Laboratory (INL),[168] and the recently completed Material Plasma Exposure Experiment at Oak Ridge National Laboratory.[169] The STAR[170] 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.[171,172]

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[173] 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.[174] 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 NRC Burning Plasma study in 2004, 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

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[167] Tynan, et al., “Mixed Material Plasma-Surface Interactions in ITER: Recent Results from the PISCES Group,” in Plasma Interaction in Controlled Fusion Devices, Benkadda (Editor). *AIP Conference Proceedings* 1237, pp. 78-91 (2010).

[168] 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).

[169] Rapp, et al., “The Development of the Material Plasma Exposure Experiment,” *IEEE Trans Plasma Sci* 44, 3456 (2016).

[170] Tynan, et al., “Mixed Material Plasma-Surface Interactions in ITER: Recent Results from the PISCES Group,” in Plasma Interaction in Controlled Fusion Devices, Benkadda (Editor). *AIP Conference Proceedings* 1237, pp. 78-91 (2010).

[171] Merrill, et al., "Modifications to the MELCOR code for application in fusion accident analyses" *Fusion Eng Design* 51–52, pp. 555-563 (2000).

[172] Taylor, et al., "Updated safety analysis of ITER," *Fusion Eng Design* 86, pp. 619–622 (2011).

[173] C. E. Kessel, et al., "The Fusion Nuclear Science Facility, the Critical Step in the Pathway to Fusion Energy," *Fusion Science and Technology* 68:2, pp. 225-236, (2015), DOI: 10.13182/FST14-953.

[174] Smolentsev, et al., “Review of Recent MHD Activities for Liquid Metal Blankets in the US,” *Magnetohydyamics* 53, 411 (2017).

(ITPA) provides an international framework for coordinated fusion research; since 2008, the ITPA operates under the auspices of ITER. [175]

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[176]), plasma diagnostics (e.g., Faraday cups), experimental operating scenarios (e.g., involvement in developing deuterium-tritium scenarios[177]), and simulation codes (e.g., TRANSP[178]). 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[179] (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 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.

U.S. Participation in Fusion Activities in Asia

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[175] See https://www.iter.org/org/team/fst/itpa.

[176] Baylor, et al., "Disruption-Mitigation-Technology Concepts and Implications for ITER," *IEEE Trans Plasma Sci* 38, 419 (2010).

[177] Budny, et al., "Predictions of H-mode performance in ITER," *Nuc. Fusion* 48, 075005 (2008).

[178] Budny, Cordey, TFTR Team and JET Contributors, "Core fusion power gain and alpha heating in JET, TFTR, and ITER," *Nuc Fusion* 56, 056002 (2016).

[179] Lazerson, et al., "Error field measurement, correction and heat flux balancing on Wendelstein 7-X," *Nuc 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 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.[180] 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.[181] 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.[182]

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.[183]

U.S. Participation in the International Tokamak Physics Activity

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).[184] 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.

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[180] 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).

[181] D.P. Schissel et al., "Remote third shift EAST operation: a new paradigm," *Nucl. Fusion* 57 056032 (2017).

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

[183] For example, Chen, et al., “Self-consistent modeling of CFETR baseline scenarios for steady-state operation,” *Plasma Phys Controlled Fusion* 59, 075005 (2017).

[184] Liu, et al., “Comparative investigation of ELM control based on toroidal modelling of plasma response to RMP fields,” *Phys Plasmas* 24, 056111 (2017).

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.”[185]

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.[186] This plan was endorsed by the 2009 NRC Committee to Review the U.S. ITER Science Participation Planning Process.[187] The 2009 NRC report further stated (p. 2), “U.S. involvement

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[185] United States Department of Energy, *The Office of Science’s Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, December 2015.

[186] USBPO, *Planning for the U.S. Fusion Community Participation in the ITER Program*, June 2006. https://www.burningplasma.org/web/ReNeW/EPAct_final_June09.pdf.

[187] National Research Council, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, 2009.

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[188] 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,[189] 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,

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[188] "Perspectives on Burning Plasma Research," Charles Greenfield and Amanda Hubbard, presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research (June 5, 2017).

[189] "Perspectives from the US ITER Project," Ned R. Sauthoff, presented to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research (August 29, 2017).

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,[190] 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.[191] 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[192] 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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[190] *Project Execution Plan for U.S. ITER Subproject-1*, DOE Project No. 14-SC-60, U.S. DOE/OS/FES (January, 2017).

[191] See slides 56-59 in Ned Sauthoff's presentation to the Committee, August 29, 2017, Ref. 23.

[192] *FUSION ENERGY: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor*, U.S. GAO Report to Congress, GAO-14-499, 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 seconds 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 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, 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.

As reported by the NRC Burning Plasma Committee in 2004, 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*,[193] *Pacing the U.S. Magnetic Fusion Program*,[194] the 1995 Report PCAST Panel on U.S. Fusion R&D Programs,[195] and *Realizing the Promise of Fusion Energy*.[196] After considering various options for a burning plasma experiment, the 2004 NRC Burning Plasma Assessment Committee[197] 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*[198] 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 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.

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[193] National Research Council, *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, 1984.

[194] National Research Council, *Pacing the U.S. Magnetic Fusion Program*, National Academy Press, 1989.

[195] President's Committee of Advisors on Science and Technology, "The U.S. Program of Fusion Research and Development," July 11, 1995.

[196] Secretary of Energy Advisory Board, *Realizing the Promise of Fusion Energy: Final Report of the Task Force on Fusion Energy*, August 9, 1999.

[197] See *Burning Plasma: Bringing a Star to Earth*, Burning Plasma Assessment Committee, National Research Council (2004), http://www.nap.edu/catalog/10816.html.

[198] National Research Council, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, 2009.

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 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.[199] 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 ITER project. Several books describe this history.[200,201,202]

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.[203]

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

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[199] For more information on inertial fusion energy, see National Research Council, *An Assessment of the Prospects for Inertial Fusion Energy*, The National Academies Press, 2013.
[200] Joan Lisa Bromberg, *Fusion*, The MIT Press, Cambridge, 1982.
[201] T. A. Heppenheimer, *The Man-Made Sun*, Little-Brown, Boston, 1984.
[202] T. Kenneth Fowler, *The Fusion Quest***,** Johns Hopkins Press, Baltimore, 1997.
[203] P.E. Stott, "The feasibility of using D–3He and D–D fusion fuels," *Plasma Phys Contr F* 47, 1305 (2005).

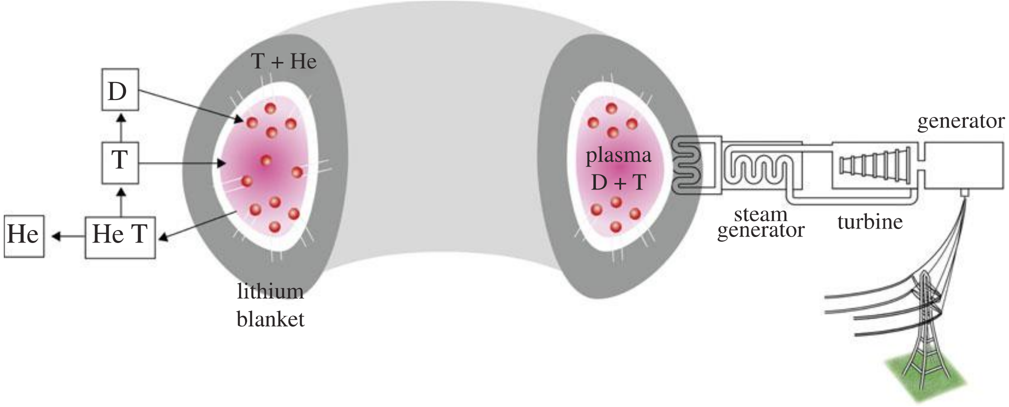

FIGURE A.1 A schematic of a magnetic fusion power plant showing (not to scale) the three parts: a hot burning plasma undergoing fusion reactions, a lithium "blanket" to capture fusion neutrons, and a heat-exchanger system with a turbine-driven electrical generator. SOURCE: C. L. Smith and S. Cowley, "The Path to Fusion Power," *Phil. Trans. R. Soc. A* (2010) 368, 1091-1108.

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 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[204] achieved 0.3 atm·sec, the Joint European Tours[205] reached 0.7 atm·sec, JT-60[206] reached 0.65, and DIII-D reached a confinement parameter of $P\tau_E \sim 0.5$ atm·sec.[207]

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-confinement mode," of tokamak operation, was discovered experimentally in the 1980's[208,209] 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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[204] Hawryluk, et al., "Results from deuterium-tritium tokamak confinement experiments," *Rev. Mod. Phys.* 70, 537 (1998).

[205] Keilhacker et al., "High fusion performance from deuterium-tritium plasmas in JET," *Nuc Fusion* 39, 209 (1999).

[206] H. Kishimoto, et al., "Advanced tokamak research on JT-60," *Nuc Fusion* 45, 986 (2005).

[207] Lazarus, et al., "Higher fusion power gain with profile control in DIII-D tokamak plasmas," *Nuc Fusion* 37, pp. 7-12, (1997).

[208] 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).

[209] 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:

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[210] 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

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[210] 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.

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.

C

Agendas from Committee Meetings

Meeting #1
Committee on a Strategic Plan for U.S. Burning Plasma Research
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
Committee on a Strategic Plan for U.S. Burning Plasma Research
August 29-31, 2017

Beckman Center of the National Academies
100 Academy Way
Irvine, California 92617

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

D

Previous Studies of Magnetic Fusion Energy and Strategies for Fusion Energy Development Consulted by the Committee

National Research Council, *Cooperation and Competition on the Path to Fusion Energy: A Report*, National Academy Press, 1984.

U.S. Department of Energy, *Magnetic Fusion Program Plan*, DOE/ER-0214, February 1985.

Energy Research Advisory Board to the U.S. Department of Energy, "Report of the Technical Panel on Magnetic Fusion," November 1986.

National Research Council, *Pacing the U.S. Magnetic Fusion Program*, National Academy Press, 1989.

Fusion Energy Advisory Committee, "Final Report," September 1990.

Fusion Energy Advisory Committee, "Report on Program Strategy for U.S. Magnetic Fusion Energy Research," DOE\ER-0572T, September 1992.

President's Committee of Advisors on Science and Technology, "The U.S. Program of Fusion Research and Development," July 11, 1995.

Fusion Energy Advisory Committee, "A Restructured Fusion Energy Sciences Program," January 27, 1996.

Fusion Energy Sciences Advisory Committee, "Review of the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report," April 18, 1997.

Fusion Energy Sciences Advisory Committee, "Recommendations on the Nature and Level of U.S. Participation in the International Thermonuclear Experimental Reactor Extension of the Engineering Design Activities," DOE/ER-0720, January 1998.

Fusion Energy Sciences Advisory Committee, "Opportunities in the Fusion Energy Sciences Program," June 1999.

President's Committee of Advisors on Science and Technology, "Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation," June 1999.

Secretary of Energy Advisory Board, "Realizing the Promise of Fusion Energy: Final Report of the Task Force on Fusion Energy," August 9, 1999.

Fusion Energy Sciences Advisory Committee, "Report of the FESAC Panel on Priorities and Balance," September 13, 1999.

Fusion Energy Sciences Advisory Committee, "Report of the Integrated Program Planning Activity for the DOE Fusion Energy Sciences Program," DOE/SC-0028, September 2000.

National Research Council, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, National Academy Press, 2001.

Fusion Energy Sciences Advisory Committee, "Review of the Fusion Theory and Computing Program," August 2001.

Fusion Energy Sciences Advisory Committee, "Review of Burning Plasma Physics," DOE/SC-0041, September 2001.

Report from the 2002 Fusion Summer Study, "2002 Fusion Summer Study Report," Snowmass, Colorado, July 8-19, 2002.

Fusion Energy Sciences Advisory Committee, "Report of the Fusion Energy Sciences Advisory Committee Burning Plasma Strategy Panel: A Burning Plasma Program Strategy to Advance Fusion Energy," September 2002.

Fusion Energy Sciences Advisory Committee, "Report of the Fusion Energy Sciences Advisory Committee Fusion Development Path Panel: A Plan for the Development of Fusion Energy," March 2003.

National Research Council, *Burning Plasma—Bringing a Star to Earth*, National Academy Press, 2004.

Fusion Energy Sciences Advisory Committee, "Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program," April 2005.

U.S. Burning Plasma Organization, *Planning for the U.S. Fusion Community Participation in the ITER Program*, June 7, 2006. https://www.burningplasma.org/web/ReNeW/EPAct_final_June09.pdf.

Fusion Energy Sciences Advisory Committee, "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy," October 2007.

National Research Council, *Plasma Science: Advancing Knowledge in the National Interest*, The National Academies Press, 2007.

National Research Council, *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*, The National Academies Press, 2009.

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.

Research Needs for Magnetic Fusion Energy Sciences, Report from the DOE Workshop Held June 8-12, 2009.

Executive Office of the President, President's Council of Advisors on Science and Technology, "Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy," November 2010.

Fusion Energy Sciences Advisory Committee, "Materials Science and Technology Research Opportunities Now and in the ITER Era: A Focused Vision on Compelling Fusion Nuclear Science Challenges," February 2012.

Fusion Energy Sciences Advisory Committee, "Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era," February 2012.

Fusion Electricity: A roadmap to the realization of fusion energy, European Fusion Development Agreement, November 2012.

Fusion Energy Sciences Advisory Committee, "Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program," February 10, 2013.

Fusion Energy Sciences Advisory Committee, "Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science," March 21, 2013.

Fusion Energy Sciences Advisory Committee, "Report on Strategic Planning: Priorities Assessment and Budget Scenarios," December 2014.

On Plasma Materials Interactions: Report on Scientific Challenges and Research Opportunities in Plasma Materials Interactions, Report from the DOE Workshop Held May 4-7, 2015.

Integrated Simulations for Magnetic Fusion Energy Sciences, Report from the DOE Workshop Held June 2-4, 2015.

On Transients in Tokamak Plasmas: Report on Scientific Challenges and Research Opportunities in Transient Research, Report from the DOE Workshop Held June 8-11, 2015.

United States Department of Energy, *The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective*, Report to Congress, December 2015.

United States Department of Energy, *U.S. Participation in the ITER Project,* Report to Congress, May 2016.

Project Execution Plan for U.S. ITER Subproject-1, DOE Project No. 14-SC-60, U.S. DOE/OS/FES, January 2017.

"Overview of the present progress and activities on the CFETR," Yuanxi Wan, et al. (2017) *Nucl. Fusion* 57 102009.

"European DEMO design strategy and consequences for materials," G. Federici, et al. (2017) *Nucl. Fusion* 57 092002.