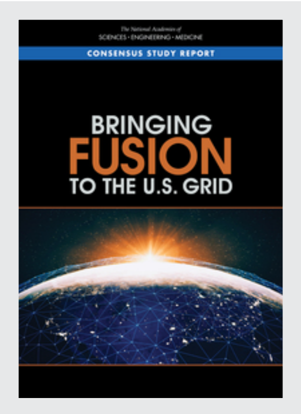

Bringing Fusion to the U.S. Grid (2021)

DETAILS

124 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-68538-2 | DOI 10.17226/25991

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SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine. 2021. *Bringing Fusion to the U.S. Grid*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

BRINGING FUSION TO THE U.S. GRID

Committee on the Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant

Board on Physics and Astronomy

Board on Energy and Environmental Systems

Division on Engineering and Physical Sciences

Nuclear and Radiation Studies Board

Division on Earth and Life Studies

National Academy of Engineering Office of Programs

A Consensus Study Report of

The National Academies of

SCIENCES · ENGINEERING · MEDICINE

THE NATIONAL ACADEMIES PRESS

Washington, DC

www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This study is based on work supported by Contract DE-SC0020922 with the Department of Energy. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any agency or organization that provided support for the project.

International Standard Book Number-13: 978-0-309-68538-2
International Standard Book Number-10: 0-309-68538-9
Digital Object Identifier: https://doi.org/10.17226/25991

Copies of this publication are available free of charge from

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National Academies of Sciences, Engineering, and Medicine
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Printed in the United States of America

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2021. *Bringing Fusion to the U.S. Grid*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

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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:

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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 C. Paul Robinson, NAE, Sandia National Laboratories (retired), and Steven J. Zinkle, NAE, University of Tennessee, Knoxville. 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.

Preface

The combination of scientific progress in fusion and the changing electrical landscape in the United States has motivated this study to examine the key goals and innovations needed to build a fusion pilot plant. The 2019 National Academies of Sciences, Engineering, and Medicine report of the Committee on a Strategic Plan for U.S. Burning Plasma Research described the progress in fusion and developed a strategic plan to guide implementation of its two main recommendations:

- First, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.
- Second, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.[1]

The second recommendation motivated, in part, this study. The other motivation is associated by the changes in the electrical industry due to the ongoing transition to low-carbon and non-carbon emission technologies that has resulted in increased fusion funding from private investors. A consensus is building across

[1] National Academies of Sciences, Engineering, and Medicine, 2019, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*, The National Academies Press, Washington, DC, doi: https://doi.org/10.17226/25331, p. 1.

the country that the nation needs to establish a low-carbon emission energy mix by 2050, and utilities are using an inclusive strategy to achieve this goal. A pilot plant is a major step on the pathway to commercialization. While it is not necessary for a fusion pilot plant to demonstrate all aspects of a first-of-a-kind commercial power plant, it must enable an understanding of material issues, including estimated replacement frequency and waste disposal, safety considerations, environmental considerations, etc., prior to construction of a commercial first-of-a-kind facility. Furthermore, the combination of experience with constructing the pilot plant and operating it should provide the developers of fusion power plants and the owner/operators with the information needed to assess the economic attractiveness and the role of fusion in the marketplace. Thus, the pilot plant needs to address the scientific and technological issues to produce electricity and to identify a pathway to an attractive energy source.

The Department of Energy (DOE) requested that the National Academies address the following:

- In developing and carrying out a plan for building a Pilot Plant, key goals need to be established for all critical aspects of the Pilot Plant. Identify those key goals, independent of confinement concept, which a Pilot Plant must demonstrate during each of its anticipated phases of operation.
- List the principal innovations needed for the private sector to address, perhaps in concert with efforts by DOE, to meet the key goals identified in the first bullet.

In response to this request, the Committee on the Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant was established. The committee's statement of task is given in Appendix A. The committee was asked to consider the phases of operation in considering the key goals and was encouraged "to seek input from potential 'future owners' of power plants, such as electric utility companies, and potential manufacturers of fusion power plant components."

In support of the Statement of Task, the time duration for committee deliberations was compressed to about 3 months from the first organizational meeting to issuing a draft report for review. This committee conducted all of its meetings virtually due to the pandemic. The fusion community was able to participate as observers in the open meetings when external speakers and panelists met with the committee. This report represents the consensus of the committee after four open meetings (see Appendix B for the meeting agendas) and weekly or more frequent meetings. The first two open meetings included representatives from DOE, including Chris Fall, Scott Hsu, John Mandrekas, Gene Nardella, and James W. Van Dam, and with congressional aides including Adam Rosenberg and Hillary O'Brian, who provided insight into the context of the study. Also, Michael Mauel, the co-chair of the Committee on a Strategic Plan for U.S. Burning Plasma Research, described the 2019 report. Two days of panel discussions were held with leaders and subject-matter experts in the following areas: licensing, including Marc Nichol, Bill Reckley, and Gary Becker; power plant owners and operator interest, including Brad Adams, Dave Christian, Ralph Izzo, and Tina Taylor; developers of fusion power plants, including Michl Binderbauer, Mike Delage, Andrew Holland, David Kingham, Bob Mumgaard, and Brian Nelson; universities, including Jean Paul Allain, Saskia Mordijck, John Sarff, and George Tynan; component manufacturers, including Muhammad Fahmy, Alexander Molodyk, Bill Shingler, and Tony Taylor; and national laboratories, including Dave Babineau, Steven C. Cowley, Corey McDaniel, and Mickey R. Wade. We are very grateful for everyone who took time away from their busy schedules to present to the committee and answer our questions. The discussions were very interesting and valuable to the committee.

During the committee's study, we received encouragement and support from many individuals to whom we are indebted; these include James W. Van Dam of DOE's Office of Fusion Energy Sciences, Scott Hsu of ARPA-E, Jill Dahlberg as a member of the Board on Physics and Astronomy (BPA), and James Lancaster, director of the BPA.

On a more personal note, I would like to express my sincere appreciation to all members of the committee for their dedicated efforts in preparing this report under a tight timeline despite other major responsibilities. I would also like to express our appreciation to the staff of the National Academies, particularly to Christopher Jones, for his advice and support through all phases of this project and making the impossible happen.

Richard J. Hawryluk, *Chair*
Committee on the Key Goals and Innovations
Needed for a U.S. Fusion Pilot Plant

Contents

Executive Summary

Fusion energy offers the prospect of addressing the nation's energy needs and contributing to the transition to a low-carbon emission electrical generation infrastructure. With the major fusion burning plasma experiment known as ITER scheduled to begin operations within the next decade, many partner countries are already undertaking large efforts to capitalize on their involvement in the international ITER experiment and position fusion as a future energy source. Technology and research results from U.S. investments in ITER, coupled with a strong foundation of research funded by the Department of Energy (DOE), position the United States to begin planning for its first fusion pilot plant. Strong interest from the private sector is an additional motivating factor, as the process of decarbonizing and modernizing the nation's electric infrastructure accelerates and companies seek to lead the way.

Published in 2019, the National Academies of Sciences, Engineering, and Medicine report *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research* (hereafter the "*Burning Plasma* report") identified research priorities for magnetically confined plasma research in the United States. In order to reach its conclusions and recommendations, the study gathered input from academia, government, and industry through numerous white papers, town halls, and site visits. The report recommended that the United States remain committed to its investment in ITER, and that

> The United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.

In a request from DOE, the National Academies' Committee on the Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant was asked to build upon the work of the *Burning Plasma* report by identifying the key goals and innovations—independent of confinement concept—that are needed to support the development of a U.S. fusion pilot plant during each of its phases of operation. The committee obtained valuable input from a broad range of stakeholders, including DOE agency staff, congressional aides, regulators, power plant owners, developers of fusion power plants, manufacturers of components, national laboratory leaders, and university researchers and professors, to address the statement of task. Relative to the *Burning Plasma* report, this committee took a somewhat different approach to examine pathways to a pilot plant by reviewing the implications of the changing electrical landscape on how fusion can contribute to the national energy needs and taking into account that private industry is looking at a broad range of fusion concepts. The committee did not evaluate specific fusion concepts.

The U.S. fusion community has been a pioneer in fusion research since its inception and now has the opportunity to bring fusion to the marketplace. On one hand, the U.S. community has not yet fully removed the risks associated with overcoming the economic, funding, technology, and safety concerns remaining before utilizing fusion as an energy source, and future difficulties may yet remain. On the other hand, the United States currently faces strong competition from other groups around the world, and if the nation can overcome these risks and provide the resources for a fusion pilot plant as outlined in this report, it has the opportunity to play a global leadership role.

Discussions with utility owners identified that utilities are planning on making major changes to the mix of electrical generation infrastructure to reduce carbon emission by 2050. The foreseen increased investment in modernizing their electrical production fleet provides an opportunity for fusion to contribute. This led to the committee's first recommendation.

Recommendation: For the United States to be a leader in fusion and to make an impact on the transition to a low-carbon emission electrical system by 2050, the Department of Energy and the private sector should produce net electricity in a fusion pilot plant in the United States in the 2035-2040 time-frame. (Chapter 2)

The committee identified key goals and innovations for a pilot plant based on the input from stakeholders received during the study as well as input received during the *Burning Plasma* study and the recent APS-DPP Community Planning Process. The key goals, if successfully met, would provide the scientific, technological, and economic information that would enable fusion power plant developers and utilities to move forward with a commercial fusion power plant. A great deal of scientific and technological progress has been made, but significant remaining technical and scientific issues must be addressed in parallel with developing a successful pilot plant design that would enable an economically attractive power plant. There is increased risk associated with this approach, as compared to solving technical and scientific issues prior to designing a pilot plant, but urgency in clean energy needs, coupled with the promise of fusion energy, motivates this approach.

Due to the highly integrated nature of a pilot plant—including cutting-edge research, technology, and engineering—a conceptual design leading to an engineering design is required. The teams responsible for the design require a breadth of talent found in industry, national laboratories, and universities. An engineering design is the basis for determining costs and developing a schedule, which is critical for project planning and execution and will provide a focus for the work. The creation of national teams is imperative to begin the design work and to identify critical technology requirements. This led to the committee's second recommendation.

> **Recommendation: The Department of Energy should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps and lead to an engineering design of a pilot plant that will bring fusion to commercial viability. (Chapter 5)**

In this report, the innovations needed for a pilot plant are broadly described. While some of the technology innovations are applicable to multiple fusion concepts, some concept-specific innovations need to be further defined. This report presents a strategic plan to help meet the key goals and generate the required scientific and technological innovations to produce electricity in the 2035-2040 timeframe. This plan identifies both goals for the various phases of design, construction, and operation of a pilot plant and broad criteria for moving forward to the next phase. This plan is more aggressive, thus higher risk, than that in the *Burning Plasma* report, since it is motivated by the needs of the electrical marketplace to make significant investments in low-carbon and non-carbon emission electricity. This results in the following conclusion:

> **Conclusion:** Successful operation of a pilot plant in the 2035-2040 timeframe requires urgent investments by DOE and private industry—both to resolve the remaining technical and scientific issues and to design, construct, and commission a pilot plant. (Chapter 5)

1

Introduction

The 2019 National Academies of Sciences, Engineering, and Medicine report of the Committee on a Strategic Plan for U.S. Burning Plasma Research, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*[1] (hereafter the "*Burning Plasma* report"), presented guidance on a strategic plan for a U.S. research program of burning plasma science and technology directed toward realizing economical fusion energy. While it recognized and described significant scientific and engineering challenges, that report concluded that the knowledge developed through decades of fusion research is now sufficiently advanced to propose a path to demonstrate fusion-generated electricity within the upcoming decades. It described a strategic plan for fusion research to guide the implementation of its two main recommendations:

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

The *Burning Plasma* report was a major input to the development of a long-range strategic plan for the Department of Energy (DOE) Fusion Energy Sciences (FES) Program. The Fusion Energy Sciences Advisory Committee (FESAC) was charged to undertake a new long-range strategic planning activity in November 2018. The "strategic planning activity—to encompass the entire FES research portfolio (namely, burning plasma science and discovery science)—should identify and prioritize the research required to advance both the scientific foundation needed to develop a fusion energy source, as well as the broader FES mission to steward plasma science."[2] A two-phase process, similar to that used by both the High Energy Physics program and the Nuclear Physics program within the Office of Science, was conducted. In the first phase, a very broad community planning process was conducted by the APS-DPP, which was completed in March 2020.[3] This planning process encompassed a much broader range of plasma physics and fusion topics than considered by the *Burning Plasma* committee. An underlying and recurrent theme of the section on fusion science and technology, which addressed the burning plasma science topics, was how the research would impact the development of a pilot plant. In the section regarding fusion science and technology, the community stated that its mission is to "establish the basis for the commercialization of fusion energy in the United States by developing the innovative science and technology needed to accelerate the construction of a fusion pilot plant at low capital cost." A FESAC panel headed by Troy Carter is completing the second phase of the planning process and will issue its recommendations on the priorities for an optimized FES program over the next 10 years (FY 2022-2031) under different budget scenarios. The FESAC report was not available to this committee prior to submitting its report for review.

In parallel with the FESAC long-range strategic planning process focused on the next decade, DOE asked the National Academies to assemble a committee to provide guidance to DOE and others that is aligned with the objectives of constructing a pilot plant in the United States that produces electricity from fusion at the lowest possible capital cost. In this report, the Committee on the Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant is to address the following:

- In developing and carrying out a plan for building a Pilot Plant, key goals need to be established for all critical aspects of the Pilot Plant. Identify those key goals, independent of confinement concept, which a Pilot Plant must demonstrate during each of its anticipated phases of operation.
- List the principal innovations needed for the private sector to address, perhaps in concert with efforts by DOE, to meet the key goals identified in the first bullet.

In doing this task, the committee was encouraged "to seek input from potential 'future owners' of power plants, such as electric utility companies and potential manufacturers of fusion power plant components, to broadly characterize the energy market for fusion and to provide input on what they would look for in a fusion pilot plant and how such plants can contribute to national energy needs." The full statement of task is given in Appendix A.

A fusion pilot plant producing net electricity should lead to a commercially viable fusion power plant by providing the information needed by utilities to design, build, license, and operate future plants. A pilot plant is not meant to demonstrate the economic viability of the commercial plant but is meant to test the technologies employed and demonstrate high-grade heat extraction to produce electricity, availability for an extended period, and fuel cycle and tritium self-sufficiency; explore techniques to reduce construction and operations cost; demonstrate safe and reliable operations; and provide training to potential operators of future commercial plants. A pilot plant is not expected to operate for the full lifecycle of a first-of-a-kind power plant and thus there will be residual risks that will have to be considered. Nonetheless, the pilot plant will provide the basis for design and cost projections of a commercial power plant, which will enable the marketplace to establish the role of fusion in meeting the energy needs of the nation.

While this charge closely relates to and builds on the work by the *Burning Plasma* committee and the APS-DPP community planning process, there are significant differences in scope and emphasis. The following introduction provides a summary of the committee's approach to its task and an outline and guide to the overall structure of this final report, including the committee's findings and recommendations.

COMMITTEE APPROACH

This study was limited to 8 months, which is much shorter than the *Burning Plasma* study. In practice, 3 months elapsed from the first meeting of the committee to the submission of the draft for review. The duration of the study had several implications. In developing a plan for building a pilot plant, the committee relied primarily on past studies with limited but very valuable input from experts. Previous technical studies, as well as the results from the *Burning Plasma* report and the APS-DPP community planning report, provided significant contributions. What differentiated this study—overseen by the Board on Physics and Astronomy but in collaboration with additional boards with broader scope—was the emphasis on soliciting input from utilities, developers of fusion systems, and manufacturers of components for fusion systems as well as other community groups with a role in the development of a pilot plant. There was a previous report by members of the U.S. fusion community and utility members[4] that was written more than 20 years ago. Since then, significant changes in the electricity generation marketplace have occurred. Thus, it was necessary to review and update as appropriate the conclusions from the previous studies and take into account more recent work, including related work in fission.

The status and potential evolution of the electricity generation marketplace have many ramifications that need to be considered to properly plan, build, and operate a fusion pilot plant, ranging from new ways that fusion can contribute to including cost targets. Prior studies and inputs to the committee were important in understanding this evolving landscape and the uncertainty in forecasting the future. The emphasis on cost is an important consideration, both in the development of a pilot plant as noted by the *Burning Plasma* report and in the statement of task, but also in the eventual impact on national energy needs.

Another significant change from 20 years ago is the role of private industry seeking to develop fusion energy and companies interested in building components for fusion. These companies have the potential to play a major role in the development of fusion energy. Thus, understanding their potential role was an important input. In addition, the role of electric utilities has changed in the last 20 years with some still vertically integrated but many having their generation assets moved to another entity due to unbundling as the industry deregulated. This has impacted who can and will be able to participate in a pilot plant or the first-of-a-kind commercial plant.

The *Burning Plasma* report and the APS-DPP community planning process identified many scientific and technical issues that need to be addressed to both enable the construction of a fusion pilot plant and to reduce its cost. This committee relied heavily on those reports for the technical innovations required to develop a pilot plant. Although this recent, extensive body of work was very valuable, it did not cover all of the possible fusion concepts. *Burning Plasma* focused on magnetic fusion energy but did not address magneto-inertial concepts or inertial fusion energy (IFE). A 2013 report on the prospects for IFE also provided input.[5] The scope of the present report will be discussed further below.

The development of a low-cost fusion pilot plant will require not only scientific and technical innovations but also innovations in public policy areas to facilitate the licensing of a fusion pilot plant and the structuring of public-private partnerships to pursue this goal. Other parallel activities are under way that bear on these issues. On October 6, 2020, the Nuclear Regulatory Commission held a public meeting regarding licensing,[6] and the Fusion Industries Association has written a report on this topic.[7] The public meeting and report provided background information to the committee. Also, in April 2020, DOE announced a request for information to explore cost-share partnership programs where the funding is provided directly to the private-sector companies under a performance-based-milestone-driven approach.[8] The committee received the responses to this announcement, which provided background information.

The implication of adhering to the short timeline in the statement of task required the committee to limit the scope of the report. The key goals for a pilot plant are broadly applicable across most fusion concepts, although strongly informed by the leading fusion concept, a deuterium-tritium fueled tokamak. Some of the goals would change with a different fuel such as hydrogen and boron. While principal changes will be noted due to the choice of fuel, this report more extensively considers deuterium-tritium fuel as the baseline. Fusion concepts span a broad range from magnetic confinement to magneto-inertial to inertial confinement fusion. Some scientific and technical innovations required to construct a fusion pilot plant are largely concept independent; however, other needed innovations depend on the concept and the level of maturity of the technical and scientific basis. In considering how to allocate limited time on this topic, the proximity in terms of fusion parameter performance and pulse duration relative to that needed for a commercial power plant guided the choice to emphasize the tokamak concept for this report to illustrate the types of innovations needed.

Alternatives to the tokamak concept are being developed by both the private and public sectors. The proponents of these have identified the potential for breakthrough results that would lead to a more economical fusion reactor. Future research and discoveries may conclude that other concepts are indeed preferable, but the committee could not evaluate the different concepts or assess the implications of what innovations are needed for their success within the limited timeline. This is broadly consistent with the statement of work that the report should be independent of concept.

STRUCTURE OF THE REPORT

The following five chapters describe the committee's guidance for a plan leading to the construction of a fusion pilot plant:

- Chapter 2 describes the role of the pilot plant in the pathway to commercialization. As part of commercialization, there will be a first-of-a-kind (FOAK) fusion power plant, which will operate after the pilot plant and needs to both be technically successful and address the needs of the marketplace. Building a pilot plant at the lowest possible cost requires understanding what issues need to be resolved in support of utility owners' decision making. Understanding the utility owners' perspective was an important input in defining the key goals of a pilot plant.
- Chapter 3 describes the goals of a fusion pilot plant. A distinguishing feature of a pilot plant is that it is an integrated solution to generate net electricity that needs to be accomplished in the context of the pathway to commercialization, as discussed in Chapter 2. Thus, many key goals extend beyond integrated performance, including areas such as materials, fuel supply, reliability and availability, environmental and safety, licensing, and economic considerations. The economic considerations include not only the cost of

the pilot plant but also the pathway for an energy source that meets the nation's needs.

- Chapter 4 describes the critical innovations needed to address the key goals. The innovations will address a broad range of scientific and technical issues. This chapter also discusses the roles of the public and private sectors and models for public-private partnership to accelerate the development of fusion.
- Chapter 5 describes a strategy and roadmap for a pilot plant to address the goals in Chapter 3 and outlines an integrated plan for building a pilot plant.

NOTES

1. National Academies of Sciences, Engineering, and Medicine, 2019, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research,* The National Academies Press, Washington, DC, https://doi.org/10.17226/25331.
2. J.S. Binkley, 2018, "Fusion Energy Sciences Advisory Committee Charge Letter on Strategic Planning," updated November 30, https://science.osti.gov/-/media/fes/fesac/pdf/2018/FESAC_Charge_Letter_on_Strategic_Planning.pdf?la=en&hash=839F70008605FAE3D1BEAE5B6AE8973292FFA5DC.
3. S. Baalrud, N. Ferraro, L. Garrison, N. Howard, C. Kuranz, J. Sarff, and W. Solomon, 2020, "A Community Plan for Fusion Energy and Discovery Science," https://arxiv.org/abs/2011.04806.
4. J. Kaslow, M. Brown, R. Hirsch, R. Izzo, J. McCann, D. McCloud, B. Muston, A. Peterson Jr., S. Rosen, T. Schneider, P. Skrgic, H. Snow, and B. Snow, 1994, Criteria for practical fusion power systems: report from the EPRI fusion panel, *Journal of Fusion Energy* 13(2-3).
5. National Research Council, 2013, *An Assessment of the Prospects for Inertial Fusion Energy*, The National Academies Press, Washington, DC, https://doi.org/10.17226/18289.
6. Fusion Industry Association, 2020, "DOE/NRC/FIA Public Forum on a Regulatory Framework for Fusion," press release, updated October 2, https://www.fusionindustryassociation.org/post/doe-nrc-fia-public-forum-on-a-regulatory-framework-for-fusion.
7. Fusion Industries Association, 2020, "Igniting the Fusion Revolution in America," https://www.fusionindustryassociation.org/post/fusion-regulatory-white-paper.
8. C. Fall, 2020, Cost-sharing partnerships with the private sector in fusion energy, *Federal Register Notices* 85(76): 21842. https://www.federalregister.gov/documents/2020/04/20/2020-08312/cost-sharing-partnerships-with-the-private-sector-in-fusion-energy.

2

Role of the Pilot Plant on the Path to Commercialization

As indicated in Figure 2.1, a consensus is building across the country that the nation needs to establish a low-carbon emission energy mix by 2050, and utilities are planning to use an inclusive strategy to achieve this goal. No form of low-carbon emission energy is being ruled out at this point. As a result, the investment in low-carbon and non-carbon emission energy technologies has skyrocketed, and advances in carbon capture, energy storage, nuclear fission, and renewables are being made at a rapid pace. If fusion is to play a role in the energy mix, it will need to distinguish itself in an extremely competitive market. As such, a fusion pilot plant will need to demonstrate characteristics that can be extrapolated with low uncertainty to a first-of-a-kind (FOAK) fusion power plant that will be competitive in the energy market. Predicting the state of the energy market is complex as it depends on state and federal policies, which are influenced by many factors, such as the political landscape and the economy. Frequent communication with the potential users of the technology, the utilities themselves, may help inform these projections as market conditions change. Utility integrated resource plans can be used to estimate the characteristics that must be met by a FOAK fusion power plant. The committee received briefings and input from three electrical utility executives, which were valuable in understanding their planning for this transition.

ELECTRICAL LANDSCAPE

The current and future energy market would suggest that the United States will remain energy independent and this will continue unless disruptive events

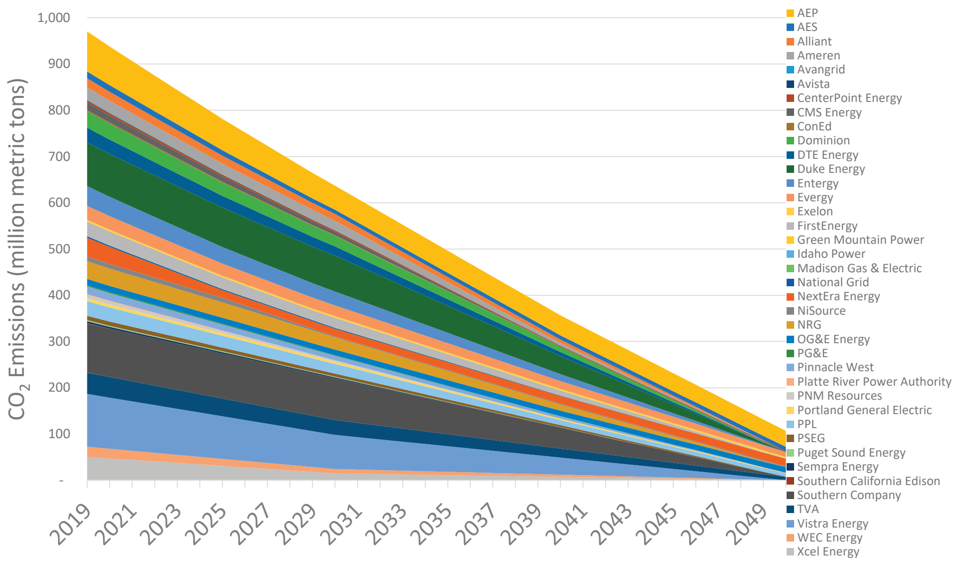

FIGURE 2.1 Illustration of the pledges from major utilities in the United States to reduce annual carbon emissions by 2050. SOURCE: Nuclear Energy Institute, ABB Velocity Suite, U.S. Environmental Protection Agency, public utility press releases. ©2020.

in policy or the geopolitical landscape occur. Changes in the generation mix are expected to continue over the next 30 years, suggesting that there will be large capital investments in both generation resources and in transmission and storage assets to accommodate the shift to low-carbon emission resources. Facilitating the low-carbon transformation and providing dispatchable power with blackstart capability competitively frames likely market opportunities for fusion generation in the foreseeable decades, if it can be developed and competitively available by the time those investments need to be made. This framing presents a window for major investment that can be captured by fusion if it can be successfully demonstrated including showing economic attractiveness. To characterize this another way: lack of a market pull could pose a challenge to the future of a commercial fusion power plant unless a fusion pilot plant with unique attributes can be successfully built prior to 2050, encouraging the development of this technology.

According to the U.S. Energy Information Administration's Annual Energy Outlook 2020 with projections to 2050,[1] electricity use will continue to grow due to increased electrification in all sectors; however, growth will likely occur at a slower rate than in the past due to increased efficiency (Figure 2.2).

At least 30 GW of additional generation resources are expected to be needed annually from 2040 to 2050 based on the reference case analysis for the United

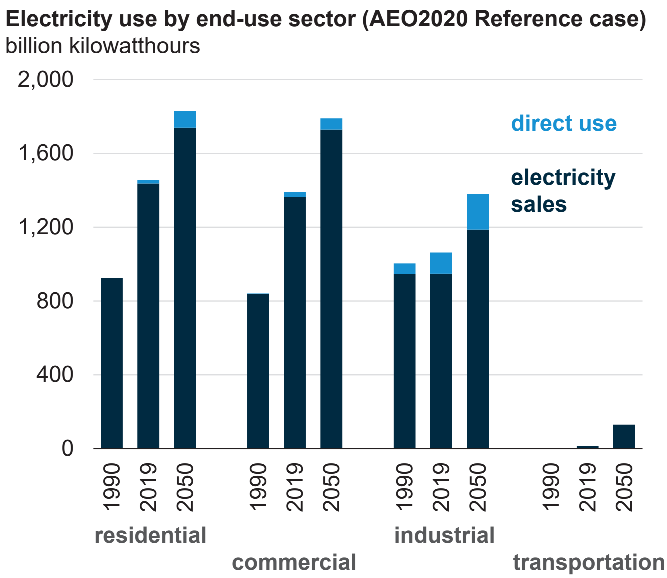

FIGURE 2.2 Projections by the U.S. Energy Information Administration's Annual Energy Outlook 2020 showing the growth in electricity use. "Direct use" is use of electricity that is self-generated, produced by either the same entity that consumes the power or an affiliate, and is used in direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment.

States. This is consistent with others' view on the exploding demand for non-CO_2 producing sources of electricity globally,[2] as shown in Figure 2.3. In the future, sources of low-carbon electricity generation that can be dispatched on demand at the request of power grid operators, known as firm dispatchable generation, will be needed. By 2050, this firm dispatchable future generation will be a competition between several forms of generation—fission, natural gas with carbon capture, renewables paired with storage and hydrogen or natural gas generation, and fusion. All will need to make sure that the electric transmission upgrades will not be prohibitively expensive for the location selected. Generation with a flexibility of siting, like fusion, will have an advantage in certain geographic areas and can enable microgrid development.[3] Microgrids will be a part of the new electricity grid and along with other sources such as renewable generation will reduce the number but not the need for baseload, firm low-carbon and non-carbon emission generation facilities to deal with the variability of loads, generation sources, weather condition impacts, and other factors discussed in this section.

This significant change of the electric energy landscape is underway today to shift to a low-carbon emission generation mix in the future. If successful, this

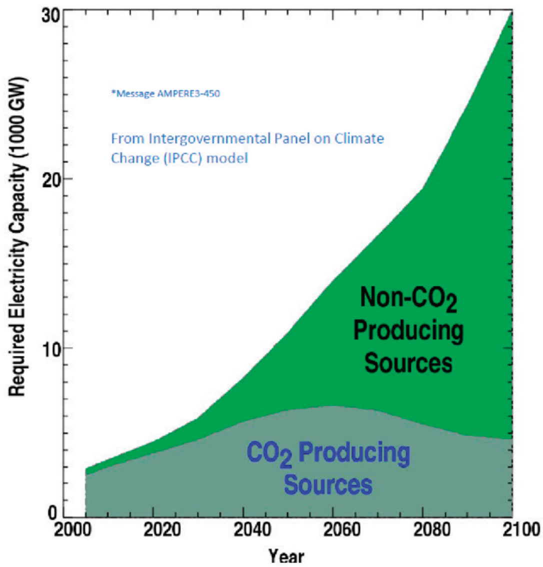

FIGURE 2.3 Projections of world electricity capacity using the Intergovernmental Panel on Climate Change model. SOURCE: M.R. Wade, Oak Ridge National Laboratory, 2020, "Exploding Demand Requires Urgency in Fusion Energy R&D," virtual presentation to the committee on Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant, based on AMPERE Public Database website, October 2020, https://tntcat.iiasa.ac.at/AMPEREDB/dsd.

change in generation from a carbon-based fuel to a low-carbon mix will likely occur due to state regulations, public policy requirements, customer preferences, and stockholder desires. A fusion pilot plant followed by a FOAK fusion power plant would be entering the electric energy market in the middle to near the end of this transformation in the United States.

Electric utilities in the future will need firm low-carbon and non-carbon emission resources in their generation portfolio if they are going to support a low-cost, lower carbon future.[4] These resources will assist with the load variability in daily grid operations by having generation and storage resources that can meet the demand in all seasons and over long durations (>4 hours) when needed, such as during severe weather events. The generation resources will include nuclear fission power plants capable of flexible operations, hydroelectric power plants with high-capacity reservoirs, coal and natural gas plants with carbon capture, geothermal power, biomass and bio-gas fueled power plants, and nuclear fusion power plants.

Presently, utilities are seeing large swings in daily operations and are using their dispatchable resources or baseload generation to manage these variable conditions. The use of high-speed electronic-controlled DC to AC systems with short-term storage, a type of Flexible AC Transmission (FACTs) device, known as STATCOMS, will continue to propagate on the transmission networks along with synchronous generators to assist with stability issues and provide the required speed for voltage or volt-ampere reactive (var) support in geographic areas where firm low-carbon emission resources are not available.

As the transmission network integrates more electronic-controlled loads and generation resources, the speed of the required network response will become faster than the four seconds that the network response has today to maintain stability. The speed of response in the future will depend on the number of firm low-carbon emission resources operating in a specific region as a percentage of the overall generation mix.

Larger grid-scale storage, such as pump storage facilities or large-scale battery installations with >4 hours of energy, will help with both short-term variability in renewable energy resources and weekly variability requirements, but the ability to cost-effectively deploy at locations needed will limit their penetration within the marketplace.

Unlike electronic-controlled generation like photovoltaic power stations, firm low-carbon emission resources will provide the inertia and fault current required for protective systems (relays, fuses) to operate as designed on the transmission and distribution systems[5] and also within existing homes and commercial and industrial buildings.

The changes in dynamic resources required for voltage or var support with renewable generation resources plus relay protection changes required will necessitate additional system modifications to accommodate the increasing penetration of renewable resources. The number of system augmentation devices needed, such as FACTs devices, will be offset by the regional installation of firm low-carbon and non-carbon emission generation resources.

In addition, the electric industry will need a diversity in baseload or firm low-carbon and non-carbon emission energy resources to offset any disruption in future fuel supplies or technology threats (e.g., cyber attacks) or changes in policy on the nation's energy landscape. The energy landscape has traditionally had disruptions that have pivoted the direction of generation production. At the beginning of power generation, the major units were either coal or hydroelectric units. This changed over time, and by the 1950s the movement away from coal production began, peaking around 1970. The 1973 oil embargo shifted generation away from oil generation and moved production back to coal and nuclear energy production. During this period, substantial pumped hydroelectric storage was deployed to help match these firm resources to variable demand. In 1979, the Three Mile Island accident slowed nuclear plant builds, and it was not until the 1990s when nuclear power had public acceptance and acceptable cost. The renaissance for nuclear power in the early 2000s was impeded after the 2011 Fukushima Daiichi nuclear accident and as a result of low natural gas prices in the United States. In 2010 the market shifted again to grid-scale photovoltaics (PV) due to a continuing decline in panel price, increased efficiency, PV subsidies, and public demand. If history is any guide, disruption in the generation market will likely occur in the future, so as we envision future generation, we need to assume that the generation mix will change and that diversity is important for national security and resiliency. The United States has had one of the most reliable electrical grids due to the diversity of fuels/sources in its generation mix, allowing the industry to pivot as disrupting events occurred. These events showed the need for fuel diversity in regulated utility generation planning and the role of the natural diversity provided by the larger interconnected U.S. electrical grid with regional fuel supply diversity. Fusion energy would help ensure that diversity continues into the next century while providing a non-carbon emission source of energy.

Significant disruptive events have routinely occurred in this sector and will likely occur in the future due to possible policy decisions, such as the potential elimination of fracking to extract natural gas or oil supplies or possible nation-state decisions on the cost or availability of critical materials required for renewable energy or energy storage systems. The potential disruption of any energy fuel source has caused the nation to deploy diverse sources of energy supply so that there is resiliency in this infrastructure that is so critical for national security. The future risk to generation from nation-states enhances the national security need for resiliency of generation types as these threats now include supply chain disruptions, electromagnetic threats, and cyber threats.

Recommendation: Electricity generation market policy and incentives should encourage a diversity of energy sources from various firm low-carbon emission generation resources including non-carbon emission fusion, in the future for baseload as part of a national strategy to ensure national security and the lowest cost path to a low-carbon emission future.

UTILITY CONSIDERATIONS

The U.S. electric industry has changed significantly over the last decades as transmission system operations have been unbundled from generation assets in many areas, which has enabled competitive developers to enter the generation marketplace. Competitive generators are not expected to be the first to develop or operate a fusion plant. Rather, to diversify risk and share cost, a fusion plant will likely be funded by a coalition consisting of the federal government, state governments, private industry and private developers, plus a group of investor-owned utilities (IOUs) with regulated generation assets.

The economic considerations for IOUs to participate in the development or operation of a pilot plant will be driven by state support (regulatory or policy), the impact on potential economic development, the value this technology may provide to the electric generation mix in the regions they serve, and their financial goals. Past pilot plants that demonstrate new generation technologies have been expensive on a cost per kW basis, typically driven by external benefits and an understanding of the potential future benefits. A few examples of past pilot plants include the Shippingport Nuclear plant, Duke's Edwardsport Clean Coal plant, Australia's Callide Oxyfuel, and Dominion Energy's Offshore Wind demonstration plant.

Technology for a pilot plant must be shown to be safe and provide good indication of the economic viability, cost certainty, regulatory certainty, reliability, and availability to future operators through the development and operation of a small-scale pilot plant. Considerations need to include upfront and ongoing maintenance requirements. This will provide confidence to key decision makers, such as the boards of directors of IOUs or public utility commissions that costs will not greatly exceed estimates prior to the start of the first commercial fusion projects.

In the 2020 Annual Technology Baseline report by the National Renewable Energy Laboratory (NREL),[6] the overnight costs for nuclear fission (moderate) are projected to decrease from $6,062/kW in 2020 to $4,916/kW in 2050,[7] and the nuclear fission industry with support from DOE is working to reduce this cost to a level more attractive to investors through its Nuclear Technology Enabling Technologies program.[8] Given the importance of minimizing operating and maintenance expenses plus associated personnel required to operate any generation asset, the same attention to the use of robotics and advanced analytics will be important considerations for a commercial fusion plant in design development. It is with this backdrop that electric utilities will be considering the cost for the first commercial fusion plant, so the benefits brought by this technology will need to justify any overnight cost premium. One such consideration will be the extent to which carbon emissions are reduced, as indicated in Figure 2.4, and the need for firm low-carbon and non-carbon emission electricity. Many researchers have reviewed the various cost consequences to reach a low-carbon emission future and have concluded that the lowest cost option is with firm low-carbon and non-carbon emission generation resources in our electricity mix.

Potential utility investors will require regulatory and cost certainty for a future fusion commercial plant plus an understanding of any cost risks associated with construction and operating and maintenance expenses. This plant will need to operate through at least one environmental cycle. This includes installation of integrated core components, fusion plant startup and operation in which the fusion environment degrades the component performance to the point where it must be replaced or repaired, and that such maintenance actions are taken to allow further operation of the plant. Operation of an environmental cycle provides information about the expected outage expenses and enables projections of both (1) the reductions for outage duration and (2) required operating and security costs for a commercial

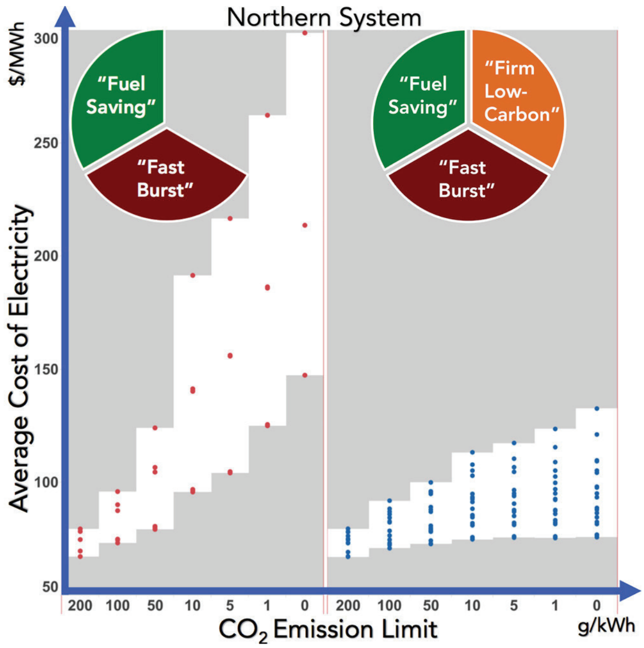

FIGURE 2.4 The cost of electricity is projected to increase as CO_2 emissions decrease; however, the inclusion of firm low-carbon emission electricity production resources consistently reduces the increase. The cost of electricity is in constant 2016 dollars. SOURCE: Reprinted from N.A. Sepulveda, J.D. Jenkins, F.J. de Sistemes, and R.K. Lester, 2018, The role of firm low-carbon electricity resources in deep decarbonization of power generation, *Joule* 2: 2403-2420, Copyright 2018 with permission from Elsevier.

facility. Characteristics for a fusion power plant that must be demonstrated by the pilot plant for electric utility acceptance through the phases of operation include safety, minimum capital cost, data for life expectancy of components, operating and maintenance expenses, acceptable emissions and waste streams, siting requirements (air and water), social acceptance, and risks related to fuel, replacement part supply chain, and insurance. Issues for fusion power plant concepts that include tritium in the fuel mixture will be discussed in Chapter 3 and need to be addressed. A pilot plant is not expected to operate for the full life cycle of a FOAK fusion power plant and thus there will be residual risks that will have to be considered. Nonetheless, the pilot plant must prove that the technology is viable and forecast economics for the commercial plant to demonstrate that the leveled cost of electricity is comparable with other available generation types, which will enable the marketplace to establish the role of fusion in meeting the energy needs of the nation.

While it is not necessary for a fusion pilot plant to demonstrate all aspects of a FOAK fusion power plant, it must enable an understanding of material issues, including estimated replacement frequency or waste disposal, safety considerations, and environmental considerations, prior to construction of a FOAK fusion power plant. This time should allow utility operators to develop procedures, estimate maintenance intervals, validate cost assumptions, perform material research, and understand longer term waste management. Given the timeline of development for the pilot and FOAK fusion power plant, the use of robotics, remote sensing, advanced analytics, and computer controls would reduce operating and maintenance costs. These advances should also provide shorter maintenance intervals and waste stream reductions as well as reduce operations and security staffing requirements. The pilot plant will be able to evaluate the impact of these advances.

ELECTRIC GRID CONSIDERATIONS

The siting of any form of generation is also a major component of capital expenditures, since siting not only involves the cost of the land but also must deal with cost uncertainty (and potential project delays) due to federal, state, and local regulatory requirements; environmental requirements such as the National Environmental Policy Act; and any infrastructure expenditures needed to either transmit electricity from the location or bring fuel to the generation location.

The electric industry is currently seeing significant cost uncertainty and delays with large electric transmission line upgrades or new installations due to public and environmental sentiment against these infrastructure projects.[9] This is expected to continue in future years, so new generation sites will need to be installed near existing transmission corridors or at locations of existing generation plants where this infrastructure is already installed.

The same cost uncertainty and potential for project time delays also are evident today for gas transmission facilities.[10] Hydrogen or natural gas generation facilities also have to contend with this same issue to ensure that gas transmission pipelines have enough capacity to support the fuel required for the generation site or that onsite gas storage is sufficient, which will significantly add to the cost of construction.

Some of the extra high voltage alternating current (EHV-AC) electric transmission corridors existing today could be repurposed for extra high voltage direct current (EHV-DC) by 2050 in an effort to bring renewable energy, such as mid-continent wind generation, to the eastern seaboard or other regions in the United States.[11] This will further encumber the existing infrastructure so that some transmission corridors may not allow for the easy siting of dispatchable firm generation due to the inability to obtain the needed export transmission lines.

The cost to build a fusion pilot plant or a FOAK fusion power plant will be reduced if placement can be made to leverage existing infrastructure. An enhanced value proposition can be made for a FOAK plant if it provides grid support functions since this plant will perform augmentation functions that the grid operator will not have to install.

In addition, the future grid will need a percentage of its generation resources to be firm low-carbon and non-carbon emission generators to successfully manage the various conditions it must support. Therefore, unique value is possible if a FOAK fusion power plant exhibits capabilities such as:

- Dispatchability
- Load following
- Onsite fuel supplies for long-duration events (>4 hours)
- Voltage or VAR support in regions
- Inertia for frequency response
- Sufficient fault current for protective equipment to function

Another requirement that will be presented over this period is the need for more blackstart capability.[12,13] The electric utility industry must have recovery plans to ensure that it can recover from major disturbances that cause the network to go completely down, including high-impact, low-probability events such as cyberattacks or electromagnetic pulse (EMP) events and extreme weather events. A blackstart generator is a unit that can start its own power without support from the grid in the event of a major system collapse or a system-wide blackout. In the United States, every North American Electric Reliability Corporation (NERC) region has its own blackstart plan and procedures. As the generation mix changes to include more renewables,[14] it challenges the existing blackstart capability that is available in the regions. Fusion has generic properties such as onsite fuel, baseload capability, and potentially dispatchable power that are attractive to blackstart. A more detailed study of specific designs and challenges to support this national security need is encouraged.

Recommendation: The Department of Energy, along with industry participants, should study blackstart requirements through 2050 and whether specific fusion power plant designs can support this national security need, either as a primary blackstart unit or secondary generating unit to aid start-up of one or more other generating units.

Without the grid support functions, additional cost will be shifted to individuals and businesses for protection changes. Transmission and distribution systems will incur additional expenses for enhanced communication requirements to operate a digital grid, increased cyber protection requirements with more digital devices, protective relay system changes to quickly isolate this new system, and additional grid augmentation devices such as FACTS devices to manage this grid.

A grid without firm low-carbon and non-carbon emission generation would increase exposure to cybersecurity threats, harmonic interaction of electronic devices, less response time for reaction to dynamic events, and an increased fragility of the network to overcome extreme events resulting in a higher cost to reach a low-carbon emission future.[15]

Finding: Dispatchable, firm low-carbon and non-carbon emission generation will be needed in the future for grid support functions and can enhance the movement to a lower carbon footprint at a lower cost.

MARKETPLACE CONSIDERATIONS

Investor owned public utilities have an obligation to serve the public in a manner that is supported by the public they serve. It is therefore important that IOUs have public acceptance for fusion energy prior to engaging in support of a fusion pilot plant or before they can pursue financial investment in a FOAK fusion power plant. This public acceptance will need to be garnered prior to the construction of a fusion pilot plant so that IOUs can have the necessary local and state support to enter this activity. Given that the fusion pilot plant is demonstrating a new technology, it will need to reinforce the confidence of the public by demonstrating safe and viable environmental operations, which includes waste disposal. The fusion industry, along with the federal government, will need to educate the public on this technology in advance of the first pilot plant so that acceptance can be realized.

The movement by electric utilities to zero-carbon generation by the 2050 timeframe indicates an opportunity window that this technology must seize if it is going to become viable as part of the mid-century generation fuel mix. A fusion pilot plant will need to go in service in the 2035-2040 timeframe to have time to demonstrate the viability and differentiation factors of fusion generation so commercial plants can participate in this new generation investment window.

At present, IOUs are not financially supporting fusion development. Investor owned utility engagement with a fusion pilot plant will require that sufficient data are delivered to move forward expeditiously (estimated at 3 to 5 years) to the construction of a FOAK fusion power plant. To provide the necessary demonstration characteristics to the future owners of a power plant as well as state or federal regulators, the pilot plant must anticipate and provide the data required for the design of a FOAK facility while minimizing the cost.

Finding: A pilot plant must provide the technical and economic information needed for utilities to operate future plants. It must serve to ensure and gauge public confidence in the technology and the success of the commercial plants that will follow.

To develop this capability at a minimum capital cost for a pilot plant, the net electricity output will likely be in the 50 MW to 100 MW range depending on technology and concept used. This output will allow for testing of the interface to a transmission system, while providing sufficient scale to support estimates for a FOAK fusion power plant. This level of electricity output includes enough data to predict availability and how it will compare to the continued improvement of nuclear fission plants at that time. The goals for the pilot plant will be discussed further in Chapter 3.

Investments in a fusion pilot plant will most likely be by a combination of government and private funding. Fusion research has historically been primarily funded by the Department of Energy (DOE), and DOE is expected to continue to play a predominant role in the development of fusion and have a major role in the development of a pilot plant. Due to the potential for electricity production, industry has become significantly involved in development of fusion concepts and technologies supporting fusion development. Funding for fusion industry developers has been rapidly growing, and fusion industry developers may play a major role in the development of a pilot plant. This development will facilitate the commercialization of fusion and the transition to a FOAK fusion power plant.

Building the U.S. fusion industry and potential investor confidence is predicated on proving the viability of technology for a sufficiently sized market opportunity. This FOAK fusion power plant will need to compete with other firm low-carbon and non-carbon emission sources of generation, and thus the estimated cost of a future plant must be competitive to firm generation sources at that time.

State and federal government support of utility involvement in the cost to build a fusion pilot plant will depend on many factors, such as public support of this technology, potential economic benefits to the region or state for future manufacturing, construction or technical jobs, or unique benefits that this technology may provide for the electric grid. Previous state and federal support for similar projects included federal grants, federal and state tax credits, cost sharing, federal government loan guarantees, federal production tax credits, and state declaration on prudency of expenditures up to a capped value for recovery of utility investment. Examples of other generation pilot plants will be discussed in Chapter 3.

FUSION ATTRIBUTES TO ADDRESS MARKETPLACE REQUIREMENTS

Fusion power generation will have an advantage in this time period if the pilot plant can demonstrate, for example, the following: load following capability, dispatchability, less long-lived radioactive waste and comparable normal radioactive effluents to fission plants, constructability for a commercial plant, reasonable staffing requirements for operations or security, licensing expectations, public acceptance, scalability to a commercial plant, and availability and reliability, which would lead to cost and regulatory certainty for the FOAK fusion power plant.

Fusion will not be unique in providing non-carbon emission energy but will be one of a handful of generation technologies during this period that may have significant national security benefits, such as an onsite fuel source, energy fuel diversity, firm non-carbon emission generation, potential ability to load follow, dispatchability, grid support functions, and a potential to aid in the blackstart[13] of the electric grid following a major disturbance.

There is also a foreign policy benefit for the United States to be the first country to deploy cost-effective fusion power as countries such as China and Russia are enhancing their global influence through export of fission power reactors. Nuclear technology is sought after by numerous developing countries due to the promise of energy security and as a means of gaining international prestige through the harnessing of a highly technical energy source.

The other benefits of fusion power plants include providing electrical system inertia, system fault current support, non-carbon emission energy, similar balance of plant features to conventional plants, higher energy density, flexible siting, a long-term source of energy, energy fuel diversity, var control, and voltage control. Fusion power also does not generate high-level waste and has the ability to become a heat source for other functions such as hydrogen production using high temperature steam electrolysis.[16] As noted in the previous section, there is also the potential benefit of contributing as either a primary blackstart unit or secondary generating unit, but this needs to be evaluated.

While demonstrating a pathway to a commercial power plant, a fusion pilot plant can also demonstrate external benefits that can be considered for a FOAK fusion power plant such as:

- Foreign policy benefit for the United States to be the first country to deploy cost-effective fusion power.
- Impact on a region's carbon reduction.
- Impact on renewable portfolio requirements by the state or region.
- Ability to ramp power output to react to variability of renewable generation swings.
- The potential to create national or regional growth and new employment opportunities for items such as plant operations, plant construction, manufacturing facilities, development of manufacturing support roles, and technical skill sets.

Recommendation: For the United States to be a leader in fusion and to make an impact on the transition to a low-carbon emission electrical system by 2050, the Department of Energy and the private sector should produce

net electricity in a fusion pilot plant in the United States in the 2035-2040 timeframe.

Recommendation: Due to the evolving energy marketplace, the characteristics of a fusion power plant should be periodically reviewed by energy experts and updated to increase the likelihood that the fusion concept will successfully contribute to the needs of society.

NOTES

1. U.S. Energy Information Administration, 2021, "Annual Energy Outlook 2020 with projection to 2050," https://www.eia.gov/outlooks/aeo/.
2. M. R. Wade, Oak Ridge National Laboratory, 2020, "Exploding Demand Requires Urgency in Fusion Energy R&D," virtual presentation to the committee on Key Goals and Innovations Needed for a U.S. Fusion Pilot Plant on October 7, 2020, Referencing data from the Intergovernmental Panel on Climate Change (IPCC) model on AMPERE Public Database website, https://tntcat.iiasa.ac.at/AMPEREDB/dsd.
3. DOE defines microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or islandmode." https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy's%20Microgrid%20Initiative.pdf.
4. N. A. Sepulveda, J. D. Jenkins, F. J. de Sistemes, and R. K. Lester, 2018, The role of firm low-carbon electricity resources in deep decarbonization of power generation, *Joule* 2:2403-2420.
5. M. J. Reno, Sandia National Laboratories, November 1, 2019, "Advanced Protection for Inverter-Based Systems," https://www.osti.gov/servlets/purl/1646214.
6. NREL, 2020, "Electricity Annual Technology Baseline (ATB) Data Download," https://atb.nrel.gov/electricity/2020/data.php.
7. Relies on U.S. Energy Information Administration (EIA) representation of current year plant cost estimates and for plant cost projections through 2050 from AEO2020 (U.S. Energy Information Administration, 2020, "Annual Energy Outlook 2020 with Projections to 2050 (No. AEO2020)," https://www.eia.gov/outlooks/aeo/pdf/AEO2020.pdf.) This report notes data are based on 2019 dollars/kW.
8. Office of Nuclear Energy, 2020, "Nuclear Energy Enabling Technologies (NEET)," https://www.energy.gov/ne/nuclear-reactor-technologies/nuclear-energy-enabling-technologies.
9. Federal Energy Regulatory Commission, June 2020, Staff report to Congress, "Report on Barriers and Opportunities for High Voltage Transmission, A Report to the Committees on Appropriations of Both Houses of Congress Pursuant to the 2020 Further Consolidated Appropriations Act," https://cleanenergygrid.org/wp-content/uploads/2020/08/Report-to-Congress-on-High-Voltage-Transmission_17June2020-002.pdf.
10. Energy Now, July 8, 2020, "The Problematic Future of Gas Pipelines," https://energynow.com/2020/07/the-problematic-future-of-gas-pipelines/.
11. U.S. Energy Information Administration, June 2018, "Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation," https://www.eia.gov/analysis/studies/electricity/hvdctransmission/pdf/transmission.pdf.

12. M. M. Adibi, G. Adamski, R. Jenkins, and P. Gill, 1995, Nuclear Plant Requirements during System Restoration, *IEEE Transactions on Power Systems* 10(3):1486-1491.
13. U.S. Department of Energy, 2019, "Hydro Plants as Black Start Resources," ORNL/SPR-2018/1077, https://www.energy.gov/sites/prod/files/2019/05/f62/Hydro-Black-Start_May2019.pdf. Pp. vi.
14. North American Electric Reliability Corporation, September 2019, "NERC Reliability Guidelines: Improvement to Interconnection Requirements for BPS-Connected Inverter-Based Resources," https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf. Pp. 18-22.
15. J. D. Jenkins, M. Luke, and S. Thernstrom, 2018, Getting to zero carbon emissions in the electric power sector, *Joule* 2:2487-2510.
16. Idaho National Laboratory Media Relations, 2020, "Private-Public Partnership Will Use Nuclear Energy for Clean Hydrogen Production," https://inl.gov/article/xcel-energy-inl-hydrogen-production.

3

Goals for a Fusion Pilot Plant

A fusion pilot plant is required to demonstrate key performance and cost metrics to directly enable first-of-a-kind (FOAK) commercial fusion power plants. This creates a set of interconnected requirements in the scientific, technical, and economic missions of a fusion pilot.

INTEGRATED FUSION AND ELECTRIC POWER PERFORMANCE

The primary goal of the pilot is to produce electricity from fusion energy. Therefore, there are basic requirements for the fusion core and the plant's electric performance.

The first requirement is that the concept must demonstrate reliable net energy gain from fusion reactions. The first hurdle is net plasma gain, Qp—that is, the ratio of fusion power to input power to the plasma, must exceed unity. It is self-evident that this objective is the minimum required for a power plant, but it is also an important threshold in fusion science since this also represents the minimum where the fusion plasma can start to heat itself in order to sustain the temperatures necessary for fusion. No fusion concept has yet met this criterion, although deuterium-tritium (D-T) tokamaks have achieved up to Qp = 0.67. The second hurdle is net plant electrical energy gain Qe, such that the amount of time-averaged electrical power generated by the fusion core exceeds the electrical power required for operation. This step requires the conversion of fusion energy into electricity taking into account the total electrical power for plasma heating, and any other forms of power required (e.g., pumps for heat removal or refrigerators), and therefore requires plasma gain well above one. Furthermore, this step requires the use of appropriate technologies to efficiently capture and convert the fusion power to electricity.

The second requirement of the pilot is that it provides cost certainty to the marketplace in terms of capital cost, construction time, control of radioactive effluents including tritium, the cost of electricity, and the maintenance/operating schedule and cost. The electrical market and fusion science guide the range of power generation in a pilot. The upper range of mature technology electrical generating units, ~400-1500 MWe, should be avoided in the pilot because these will inherently not meet the minimum cost requirement. The lower limit for a pilot is set by two considerations. First, cost certainty requires a minimum power generation scale such that the extrapolation to FOAK fusion power plant is reliable and reasonable. The FOAK power is not well defined, in part because its power level will be set by the pilot performance and marketplace considerations, but a range of 100-500 MWe appears to be a reasonable entry point for a dispatchable, centralized electricity source such as fusion. Secondly, the science of achieving sufficient Qp and Qe requires a minimum fusion power because the fusion power is also the plasma's primary heating source. While configuration dependent, most public[1] and private[2] designs for fusion plants are in the 100-500 megawatt thermal (MWth) range, which would approximately translate to a gross electric power of 40-200 megawatt electrical (MWe) assuming a conversion efficiency of 40 percent, while net electric power depends on multiple design factors including Qp, cooling power, and wall plug efficiency of plasma heating.

Finding: The pilot plant design must be based on a vetted, well-established confinement physics basis to achieve net plasma gain well in excess of unity.

Conclusion: A pilot plant must produce an amount of fusion power and energy that is sufficiently representative of the market needs in order to meet the pilot's goal of demonstrated integrated performance and cost, while also demonstrating net electricity gain Qe > 1 and producing peak net electrical power ≥50 MWe.

The third requirement of a pilot plant is the demonstration of sufficient fusion power duration that the plant is providing certainty as to the cost and viability of FOAK operation in the marketplace. The nature of fusion technology and science leads to several distinct phases of demonstration and learning for a pilot plant toward the ultimate goal of operating the pilot in a manner closely representative of FOAK operations. These phases are set by the characteristic timescales involved in the fusion system.

Finding: Regardless of concept, a fusion pilot plant generally needs to meet these phased requirements:

Phase 1a: Production of net fusion plasma energy gain (Qp ≳ 1) for many characteristic timescales of the concept. Plasma timescales can include energy and particle confinement, pulse duration, stability, particle/ash exhaust, and magnetic field distributions. Power exhaust timescales include heat transfer in plasma-facing components (PFCs) and coolants in continuous concepts, or sufficient fusion energy-producing events at repeated performance in pulsed designs.

Phase 1b: Capture and conversion of this fusion energy into electricity for the characteristic timescales for generating electricity including the blanket (in D-T systems), heat exchange, electricity generating equipment such as turbines, recirculating power, and waste heat rejection. Furthermore, this phase requires demonstrating a single closed fuel/ash cycle. For D-T concepts, this would require recovery of tritium from the blanket for insertion into the fusion plasma, although not necessarily in real time. All concepts should demonstrate sustained ash removal.

Phase 2: Production of fusion power and electricity for an environmental cycle of the components that are degraded by the fusion energy production expected in an annual operation cycle of a FOAK fusion power plant. Operation during an environmental cycle results in material erosion and migration of plasma-facing surfaces, fuel/ash transport and retention, sensors, plasma actuators, and material damage caused by energetic neutrons in D-T systems.

Phase 3: Production of fusion power and electricity for many environmental cycles or for several designs of internal components in order to fully define the lifetime and availability, and potentially optimize manufactured components of commercial fusion power plants.

Conclusion: Phase 1a should target 100-500 MW time-averaged thermal power for ≥100 s, which will exceed the characteristic plasma and power removal timescales. Phase 1a should demonstrate sufficient fusion plasma energy gain (Qp) that net electricity is feasible in subsequent pilot phases. For pulsed concepts, these facilities should operate at the design repetition rate for Phase 2.

Conclusion: Phase 1b should target ≳50 MWe peak electricity generation and time-averaged electricity generation for $\geq 10^4$ s (≥3 hours) with Qe > 1. For D-T fusion, the pilot plant should demonstrate production, extraction, and refueling of tritium on a timescale sufficient to maintain reasonable operations. For pulsed concepts, these should be for a comparable timescale of ≥3 hours at the design repetition rate for Phase 2.

Conclusion: Phase 2 should target 100-500 MW net fusion time-averaged thermal power, and ≥50 MWe peak electricity generation and Qe > 1, for a period of time that integrated fusion components demonstrate an environmental cycle. This is most likely to eventually require operation on the order of one full power year.

Conclusion: Phase 3 should target 100-500 MW net fusion time-averaged thermal power, and ≥50 MWe peak electricity generation and Qe > 1, through several environmental cycles in order to demonstrate and improve average availability for commercial fusion, provide additional data on the mean time to failure and replacement time for materials/components, and have the option to use the platform for testing advanced materials and technology and novel deployment of fusion to the grid.

MATERIALS AND MANUFACTURED COMPONENTS

It is evident from input received from electrical utilities that in order for the fusion pilot plant to provide the foundation necessary to enable a FOAK fusion power plant, the pilot plant in Phase 2 operation will need to produce continuous energy, or perhaps with a representative availability of at least 50 percent, for at least one, if not two, environmental cycle(s). An environmental cycle is characterized as a period that includes installation of integrated core components, fusion plant operation in which the fusion environment degrades the component performance to the point where it must be replaced or repaired, and that such maintenance actions are taken to allow further operation of the plant. While an environmental cycle is not strictly defined numerically, because it can vary across design approaches, based on our present knowledge base it likely represents a significant (on the order of one full power year) operational time before maintenance/repair would be required in a FOAK fusion power plant. It is important to note that this range of times would be familiar to and expected for operators of FOAK power plants in the marketplace. The requirement for operation for an environmental cycle imposes clear goals for the performance of key components. PFCs or armor, internal structural and blanket materials, power extraction systems, and breeding materials (if required) need to successfully demonstrate operation up to a global neutron or ion surface/wall loading equivalent to approximately 1 to 3 MW-year m^{-2} on the PFC armor, and approximately 2 to 3 MW-year m^{-2} on the internal structural and blanket materials. This will enable these components to experience the coupled environmental degradations arising from combinations of plasma particles, thermal loading, ionizing radiation, and high-energy neutrons. While this combination may vary across approaches, all pilot designs must account for this degradation. Table 3.1 provides goals for the PFCs and structural materials in Phase 2. Phase 2

TABLE 3.1 Goals for Material Operation During Phase 1 and 2 of a Fusion Pilot Plant

Component	Phase 1 operation	Phase 2 operation
Plasma-facing components (PFCs)/ divertor/first wall armor	• Demonstrate ability to successfully remove heat flux for durations on the order of hours/days for compact fusion pilot plant power densities • Demonstrate net erosion yield ≤1 mm/ effective full power year • Demonstrate sufficiently low tritium losses in PFCs such that external tritium inventory is maintained for power operations and effluents remain within regulatory limits • Demonstrate robustness to expected fast and thermal helium ion implantation in PFCs	• Demonstrate heat removal, material erosion, and tritium loss can be sustained for an environmental cycle • Demonstrate structural integrity for neutron wall loading on the order of 1 to 3 MW-year m^{-2}
Structural materials	• Demonstrate integrity during multiple operating cycles of relatively short duration (relatively low neutron fluence but at neutron flux comparable to Phase 2)	• Demonstrate structural integrity to a neutron wall loading up to 2-3 MW-year m^{-2} • Demonstrate remote maintenance/ replacement of components • Establish lower bound on mean time to failure of structural components
Blanket materials	• Demonstrate power extraction • Demonstrate ability to generate and recover tritium with sufficiently low tritium losses such that external tritium inventory is maintained for power operations and remain within regulatory limits	• Demonstrate tritium generation with TBR > 0.9 averaged over an environmental cycle • Demonstrate tritium losses <1 percent of tritium consumption averaged over an environmental cycle • Establish lower bound limit on mean time to failure of blanket structural materials due to environmental degradation

NOTE: Phase 3 has the same goals as Phase 2 with the addition of more environmental cycles and/or modified materials and components.

will also need to demonstrate effective remote maintenance and component replacement in order to provide greater certainty for the maintenance time and operation and maintenance costs of the FOAK fusion power plant. The combination of neutron flux, remote maintenance strategy, material properties, and facility availability will determine the duration of Phase 2 to test material degradation discussed in Table 3.1 and can vary depending on fusion concept.

The Phase 1 operation will focus on power generation for a relatively short duration in which the challenges associated with the power rate (global power, particle flux rate) are overcome but without the degradation that will occur after days of operation. Phase 1 itself is expected to have two operating sequences. The large engineering components such as magnets, vacuum vessel, and plasma heating and cooling, will need to be commissioned in a pilot. Phase 1a (Table 3.1) would focus on establishing the equilibrated fusion power performance and immediate thermal response of the PFC actively cooled components, which is their first integrated test at representative thermal conditions. The duration of plasma operation and heat exhaust would be increased within Phase 1b in order to demonstrate the ability to reach a steady rate of fusion power, capture the fusion energy, and demonstrate the capability to generate electricity. From a material and components viewpoint Phase 1 demonstrates solutions to the so-called "zero dpa (displacements per atom)" integration challenges—that is, issues centered around power generation and extraction but at sufficiently low energy/particle fluence such that the components should experience minimal degradation by the fusion environment. A list of goals for the Phase 1 operation are also provided in Table 3.1.

The Phase 2 operation focuses on achieving a full environmental cycle for the materials and components. The structural materials of the first wall and blanket will degrade under neutron bombardment. One can use a well characterized material such as low-activation ferritic martensitic alloys to estimate the requirement of this phase. Confidence exists that these materials can adequately perform up to doses of 50 dpa and 500 ppm He accumulation within the temperature range from 400 to 550°C arising from fast neutron-induced transmutation. For 14 MeV neutrons from D-T fusion, this translates to an incident neutron energy fluence of ~5 MW-year m^{-2} at the first wall surrounding the fusion plasma. The optimal materials/technology choice of other key components such as the plasma-facing components for the divertor, first wall armor, and associated active cooling methods that can meet the power exhaust, material erosion, and tritium retention requirements are less certain at this time. Therefore, the Phase 2 requirement is to meet a neutron wall loading of 1 to 3 MW-year m^{-2} on the PFC armor and 2 to 3 MW-year m^{-2} on the structural materials of the vacuum vessel and breeding blanket such that modifications to the structural materials and first wall components will be significant and measurable, but are not expected to result in failure of the components and entail their immediate replacement.

Meeting the phase 2 requirements leads to the possibility of introducing a Phase 3 of pilot plant operation that would have the goal of further defining the mean time to failure as well as providing the option to serve as a component test facility to evaluate the performance of advanced materials and technology in the complex fusion neutron environment, which includes significant cyclic stress, chemical compatibility, and neutron-induced materials degradation challenges. To enable Phase 3 operations with the mission of testing advanced technology, the pilot plant could be designed with the flexibility to replace sectors and more extensive remote maintenance capability to change out PFC/divertor, structural, and blanket components to accommodate different technologies.

Finding: Necessary and critical design features of a pilot plant will be the strategy, cost, and timescale of removing and replacing materials components degraded by the fusion environment.

The goals for material performance in pilot phases are summarized in Table 3.1.

FUEL AND ASH

Fusion produces net energy through nuclear reactions of various light isotopes that eventually result in helium. For example, our sun primarily produces energy due to the fusion of four hydrogen nuclei into a single helium nuclei, through a chain of reactions that involves the intermediate production of helium-3 and deuterium, the stable heavier isotope of hydrogen. Alpha particles are the most energetically favorable end state of fusion due to fundamental nuclear physics. Therefore, subsequent fusion of alpha particles is negligible and is considered the "ash" of fusion energy. The fact that the primary end product of fusion is a stable inert gas with no safety or disposal concerns is one of fusion energy's most attractive features.

Terrestrial fusion sources do not use stellar fuel cycles based solely on hydrogen since they are too slow and generate low power density. Other fusion fuel combinations are considered that have higher (but variable) reaction rates and immediate products. These include D-T fusion resulting in a helium and neutron, deuterium-deuterium (D-D) fusion producing helium-3 (also stable), tritium, neutrons, and protons, deuterium-helium-3 (D-^{3}He) fusion producing alpha particles, and a proton and proton-boron (p-^{11}B) producing three alphas. The various combinations of these reactions, their immediate products, and the helium ash make up the fusion fuel cycle. The production of energetic neutrons and gamma rays results in machine activation, leading to concerns for radioactive material disposal, and material radiation damage induced degradation as discussed in the previous section.

Ash Removal

Helium ash removal is required for all fusion fuel cycles. The helium is born as a nucleus (alpha) at extremely high kinetic energies in the fusion plasma, constituting some fraction of the fusion energy. The helium ash must be removed at a steady state rate from the fusion plasma system and replaced with the fusion fuels, to maintain a constant fusion power. The helium is eventually removed as a neutral gas particle at near room temperature in a region outside of the fusion plasma, typically a pump adjacent to plasma-facing components where the helium ions are neutralized into helium atoms. The helium ash undergoes varying degrees of energy loss before impinging on the PFCs. The impingement generally poses a significant challenge to materials because helium, as an inert element, is insoluble in materials. If the helium is promptly lost to PFCs near its birth energy (3.5 MeV) it will deeply embed in materials and cause blistering and spallation that results in material loss, while also causing high local heat flux. In some configurations the helium ash is at intermediate energies (>1 keV) and this can produce helium bubbles and cavities in the material, which can degrade thermal conductivity and drive swelling of the material. In a common configuration, called the divertor, the helium is at low energies (10-100 eV) but high flux density, which causes major surface modifications such as the growth of tendrils in PFC refractory metal surfaces.

The coupled issues of ash removal and the evolving viability of PFCs due to helium bombardment will be a critical requirement to demonstrate in all fusion pilots, regardless of configuration or fuel cycle.

Conclusion: The ash removal concept has to be demonstrated in a pilot plant and should be applicable to the FOAK fusion power plant.

Conclusion: The viability of plasma-facing components to withstand the damage caused by helium ash particles should be demonstrated in a thermal and particle environment representative of a FOAK fusion power plant.

D-T Fuel Cycle

D-T is the most common fusion fuel cycle presently under consideration due to its relatively high reactivity (10 to 100 times higher than the other fusion reactions at 100 million degrees Kelvin) and high energy gain per reaction. Tritium has a short half-life of 12.3 years, decaying into helium-3, and therefore no natural source of tritium exists. In D-T fusion the resulting 14.1 MeV neutron, which carries 80 percent of the fusion energy, is slowed down in a surrounding blanket and forced to undergo another reaction, mostly with lithium-6, which produces a helium atom and a tritium atom. The ratio of tritium produced in the blanket to the D-T neutrons is called the tritium breeding ratio (TBR). TBR must be at or above unity in order to have the D-T fusion power plant sustain itself, given that its consumables are deuterium and lithium. Detailed calculations of the neutron interactions in the blanket show that TBR can exceed unity due to the presence of other neutron reactions, which also increase the thermal power by an energy multiplier M compared to fusion power (Figure 3.1). This excess is important since it is envisioned to be the source of "starting" tritium for subsequent fusion power plants.

Finding: The scale and rate of tritium use, breeding, and processing will be a major design feature and challenge of a D-T pilot, and in particular achieving an effective tritium breeding ratio >0.9 in the second phase, which is consistent with the availability of external tritium fuel for operations.

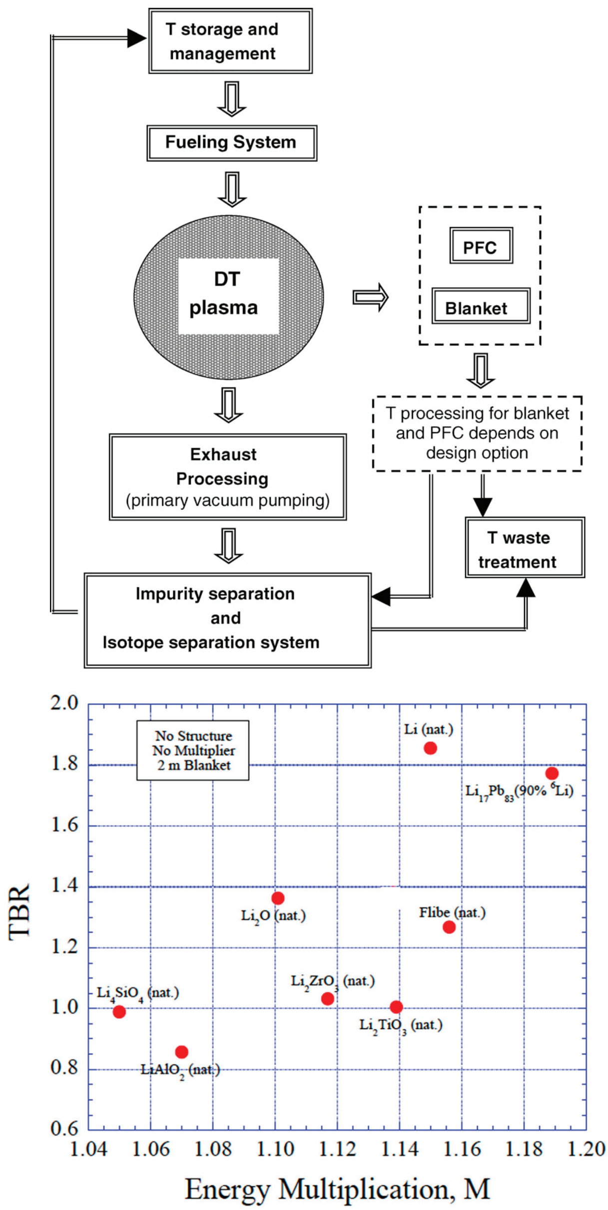

FIGURE 3.1 (*Top*) Schematic of tritium fuel cycle. (*Bottom*) Neutronics calculations for tritium breeding ratio (TBR, tritium produced per source neutron) and energy multiplier (M, thermal power/fusion power) of idealized deuterium-tritium (D-T) blankets of varying composition. SOURCE: Reprinted from M.E. Sawan and M.A. Abdou, 2006, Physics and technology conditions for attaining tritium self-sufficiency for the D-T fuel cycle, *Fusion Engineering and Design* 81:1131-1144, Copyright 2006 with permission from Elsevier.

The present world inventory of commercially available tritium is highly limited (~40 kg) and largely produced as a by-product of heavy water fission plants (Figure 3.2). While Ontario has committed to, and is in the process of refurbishing 10 of its 18 CANDU reactors, the tritium supply from CANDUs beyond the year 2040 has large uncertainty. In addition, the ITER fusion project will store ~4 kg of tritium and consume ~12 kg but not breed tritium in any significant quantity. The deployment of advanced fission reactors that could produce tritium is also unclear. The uncertain tritium production/recovery of the next 20 years, coupled to 12.3 year half-life of the tritium, motivates proceeding with the construction and operation of a pilot plant as soon as practical.

Finding: Securing sufficient tritium supplies and producing excess tritium is critical to fusion's growth path through a pilot plant to a FOAK fusion power plant to an nth-of-a-kind (NOAK) power plant.

Some advanced fission reactors, specifically fluoride salt-cooled high-temperature reactors (FHRs) and some molten salt reactors use fluoride salt coolants that contain lithium and produce tritium at rates comparable to heavy water reactors. Because these advanced fission reactors require systems for tritium control and recovery, they may have capability to extend tritium supplies and also demonstrate tritium control and recovery technologies that can be used in fusion power plants.

Finding: Advanced fission reactors that use lithium-bearing fluoride salts (such as FHRs) may provide a bridge source of tritium and demonstrate tritium control and recovery applicable to fusion power.

The rate of tritium production in a D-T pilot plant breeding blanket represents a significant step up from present commercial experiences. For example, a 500 MWth fusion system burns ~75 g of tritium per day or 28 kg/full power year. With a TBR~1 this implies the production of ~75 g tritium/day in the blanket, the recovery and processing of this tritium, and its recycling back into the D-T fusion plasma (Figure 3.1). This can be compared to the CANDU 650 MWe fission reactor, which produces ~150 g-T/year in the heavy water moderator. This tritium is periodically (~annually) removed and stored. The entire 12 GWe CANDU Ontario fleet produces ~2.5 kg/year, which due to the tritium decay results in a steady-state ~30 kg inventory, representing the majority of the world's supply. From this comparison several insights emerge.

Finding: Sufficient tritium self-production in a pilot is needed because the available world's supply of tritium is of the same order as a D-T pilot plant's annual tritium consumption. A D-T pilot plant operator will need to procure sufficient tritium to startup the facility.

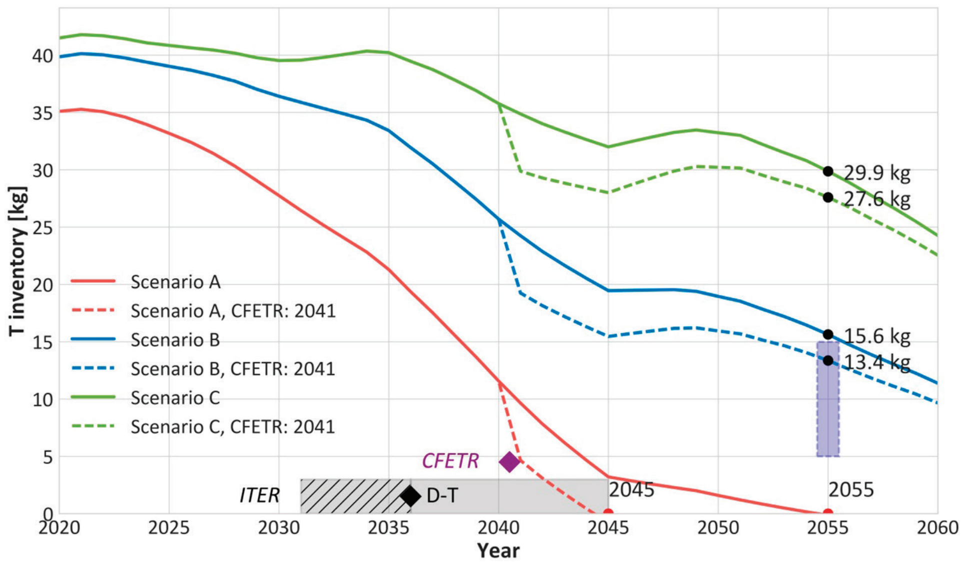

FIGURE 3.2 Projected tritium fuel inventory from heavy-water fission plants with ITER beginning deuterium-tritium (D-T) operations in 2035 with different scenarios about plant availability and T recovery ranging from pessimistic (red), to moderate (blue), to optimistic (green). CFETR is a Chinese proposed fusion experiment/pilot assumed to begin operations in 2041. The blue bar is an estimate of the start of the EU DEMO. SOURCE: M. Kovari, M. Coleman, I. Cristescu, and R. Smith, 2017, Tritium resources available for fusion reactors, *Nuclear Fusion* 58:026010, © 2017 EURATOM.

There are presently many blanket concepts being considered to meet the simultaneous demands of fusion power removal, neutron shielding, and tritium breeding. Concepts include a variety of solid and liquid blankets in various configurations to achieve these goals (Figure 3.1); however, all concepts are at low technology readiness level (TRL). Furthermore, this low readiness has to be addressed since among other reasons it has significant design implications regarding the maintenance scheme for the pilot plant. The choice of coolant and the range of operating temperature of the blanket are important for overall efficiency of the pilot plant, and this has far-reaching consequences on the design performance of the blanket. The blanket also serves as a primary component in shielding sensitive components, such as magnets, from the deleterious effects of neutrons and high-energy photons. The radial thickness of the blanket is a key consideration in setting the overall size of the fusion pilot plant.

Finding: Advancing blanket technology readiness is required in order to select the blanket concept for a fusion pilot plant.

The required inventory of tritium at a fusion pilot site depends on several design features. The first feature is the burn fraction—that is, the fraction of tritium injected into the fusion plasma that undergoes fusion. This fraction will be small because the helium ash must be kept at a low concentration (<10 percent) in the plasma and therefore most of the exhausted particles (>90 percent) are un-burned deuterium and tritium atoms, which must be processed and put back into the plasma. Burn fractions can be as low as 1 percent, which would necessitate 7,500 g of tritium to be processed per day at 500 MW fusion power. Developing a direct purification and recycle loop (i.e., direct internal recycle) as closely coupled as possible to the fusion device would be the most effective way to reduce fuel cycle building inventory. The removal of ash and non-fuel impurities in this process stream is difficult and has to be addressed.

Finding: Innovations in boundary plasma science, fueling technologies, and gas processing will be important for a pilot plant to decrease the cost and scale of tritium processing equipment.

The second important feature is the characteristic timescale to process the exhausted D-T mix and the tritium recovered from the blanket. The third design feature is the amount of tritium that is retained in materials inside the fusion reactor such as PFCs and blanket materials. Tritium permeates all materials to various degrees, so tritium confinement barriers are a necessity as the large components of the core could accumulate a significant quantity of tritium. Together these features determine the tritium residing in the plant because the tritium fuel in the plasma core is negligible (<1 g). Furthermore, they define the required minimum "starting" inventory of tritium fuel, which is important for the plant's power availability in case of a shutdown or for the start of a new fusion power plant. There is a strong motivation to decrease tritium site inventories at a pilot to decrease the licensing burden, improve safety, and enable easier start and restart of a pilot and fusion power plants.

Finding: It will be desirable for a D-T pilot plant to have a tritium inventory ≤1 kg, which reduces the release potential, offers more flexibility for siting, and reduces the demands on the external tritium supply.

Tritium purification, handling, isotope separation, and storage have historically been developed as batch or semi-continuous processes since these are cost-effective approaches for the relatively low processing rates required for non-fusion applications. The need to demonstrate continuous operation of these systems in a D-T fusion pilot plant will also likely require continual operation of the tritium processing system, which has not yet been demonstrated. Effective recovery of tritium from the blanket is an important part of tritium processing. Permeation, solubility, and materials handling issues with lithium-containing metals and salts will need to be resolved since all blanket concepts face challenges and presently have low TRL.

Finding: A fusion pilot's integrated tritium processing rate will be 10-100x faster per day than present experience in heavy-water moderated fission.

Recommendation: The Department of Energy should establish and demonstrate efficient tritium processing technologies at relevant rates and processing conditions before operation of a pilot plant.

Strict tritium management will be required for a D-T fusion pilot plant to meet regulatory controls and site limits, ensure compliance with safety bases, and maintain continuous facility operation. Previous operational experience with tritium in fusion facilities has been limited to Tokamak Fusion Test Reactor (TFTR) and Joint European Torus (JET), where the lifetime inventories were ~100 g. Tritium accountability for these machines was burdensome. A D-T pilot plant will have a tritium throughput of several kilograms a day and will have tritium breeding in the blanket. ITER's tritium accountancy process requires collection of all the tritium into hydride beds for calorimetry, which is not directly feasible for a continuously operating pilot plant.

Finding: The requirements for tritium accountability in a fusion pilot plant must be clearly defined along with analytical methods that can satisfy accountability requirements.

Alternative Fuel Cycles to D-T

The technology challenges that face alternative fuel cycles are less defined because most research efforts to date have concentrated on the D-T cycle. Nonetheless, alternate fuel cycles have been proposed and studied such as D-D and p-^{11}B that have abundant terrestrial fuel sources, and D-^{3}He, which would likely require a lunar source of He-3 for a FOAK fusion power plant. The U.S. He-3 inventory is ≈20 kg and would be capable of producing ≈400 MWth-y. Additional inventory would be required for the processing system. This quantity of He-3 appears to be sufficient to complete Phase 2 of the pilot operation for the minimum electrical power but may limit Phase 3. There are additional resources available of He-3 from the decay of tritium produced in the CANDU reactors, but these have not been assessed.

The most significant design advantage of these alternate fuel cycles is removing the requirement for tritium production/breeding and recovery from the reactor blanket. Conversely these fuels have hundred-fold lower reactivity rates at 10 keV (100 million degrees Kelvin) where D-T achieves net energy gain, and therefore alternate fuels require both higher plasma operating temperature and much higher triple product (Figure 3.3).

As well, Figure 3.3 shows that alternate fuels have a lower fraction of fusion power released as neutrons. In some fuel cycles varied amounts of tritium are produced, and in all the fuel cycles some neutrons are produced either directly (D-D) or as side reactions that occur in the plasma, and therefore issues associated with tritium (radiological safety) and neutrons (activation, volumetric damage) are not eliminated but reduced to a variety of degrees. These alternate fuel neutrons are also of lower energy than those produced by D-T, decreasing transmutation rates, especially ^{4}He production. Therefore, alternate fuels feature lower demands on neutron tolerant materials, activation, and tritium safety than D-T. Conversely the alternate fuels face more severe global design challenges for PFC surface heat removal since a larger fraction of the fusion energy is released as charged particles or photons (neutrons volumetrically heat a D-T blanket). Alternate fuel cycles often feature concepts that use open magnetic topologies and linear systems in order to meet this challenge, yet these have less experimental vetting than closed magnetic topologies. Direct energy conversion that converts the charged particle and plasma radiation directly to electricity is an example of an innovative technology that

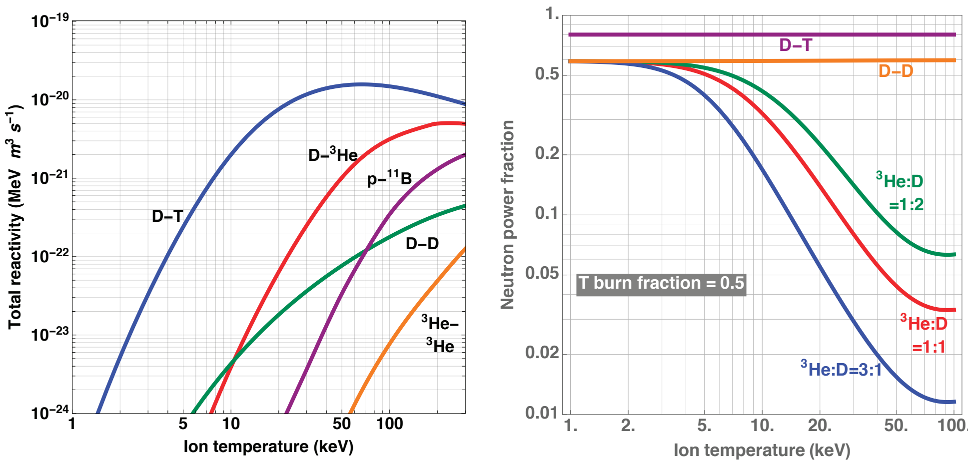

FIGURE 3.3 The reaction cross-section times the total energy released from the most studied advanced fusion fuels (1a). The total fusion energy released in neutrons from three of the most studied advanced fusion fuels (1b). NOTE: Data from H.S. Bosch and G.M. Hale, 1992, Improved formulas for fusion cross-sections and thermal efficiencies, *Nuclear Fusion* 32:611; W.M. Nevins and R. Swain, 2000, The thermonuclear fusion rate coefficient for p-^{11}B reactions, *Nuclear Fusion* 40:865; and R. Feldbacher, 1987, "IAEA Report INDC(AUS)-12/G," *The AEP Barnbook DATLIB*, Version 1. SOURCE: Courtesy of John Santarius, University of Wisconsin, Madison.

could be applied to this challenge. Technology and science innovations must also be compatible with helium ash control and removal.

Finding: The use of alternate fusion fuels removes the need for tritium breeding and reduces the requirement for neutron-tolerant materials in a fusion pilot plant.

Finding: The use of alternate fuels requires much higher ion temperatures and fusion triple product than D-T in a fusion pilot plant, and will likely require novel surface energy removal technology and configurations.

RELIABILITY AND AVAILABILITY

The pilot plant should provide operational and test data needed to assure reliability for the subsequent FOAK fusion power plant, which must be capable of operating with high availability (eventually greater than 85 percent). High reliability and availability will be an expectation for commercial customers based upon performance now achieved by existing fission power plants. A major focus for reliability will be to achieve very low forced outage rates. Scheduled maintenance outages for repairs, refurbishment, and component replacements are expected and accepted, because they can be scheduled during periods of seasonal low energy demand. But the ability to complete scheduled maintenance outages expeditiously, in time periods of several weeks will be preferred.

Reliability involves both short-term and long-term phenomena. Operations in the pilot plant should be expected to occur in phases, including commissioning, initial low power, and transient testing (Phases 1a/1b). An important point is that full tritium self-sufficiency is not required during this phase. However, subsequently the pilot plant must operate at full power in Phases 2 and 3 with availability greater than 50 percent to demonstrate reliability of those components that require periodic replacement through at least one full environmental cycle. Operating durations beyond one full environmental cycle will enable assessment of component lifetimes and assessment of the replacement/repair times and cost. Tritium consumption for D-T systems during this phase will be sufficiently large that complete, or nearly complete, tritium self-sufficiency is required. Alternate fuels will not be subject to this tritium breeding requirement. Significant upgrades and plant modifications may occur between these phases.

Modern approaches to reliability engineering, including computational modeling and engineering analysis to simulate plant assembly, operations, and maintenance, that incorporate best practices and lessons learned from large-scale project construction and systems integration to perform engineering computer aided design, structural analysis, and process and control modeling should be applied and demonstrated. Fusion components such as plasma-facing components, the structural materials for the vacuum vessel, shielding and blanket modules operate under severe thermal and radiation environments. Substantial research and development (R&D) has been devoted to structural materials performance under neutron irradiation for these components, but design and integration into a functioning fusion power plant is highly complex and is one of the primary objectives of a pilot plant.

Finding: A fusion pilot plant will need to demonstrate the ability to efficiently perform remote maintenance and replacement in support of the design of a power plant, taking into account details of the consequences of the fusion environment, such as material activation and tritium retention in components.

Finding: The use of modular, replaceable components will be a highly desirable design feature in a pilot plant to improve its ability to test critical components and achieve high availability.

ENVIRONMENTAL AND SAFETY CONSIDERATIONS

Fusion provides the promise of a safe and environmentally acceptable energy source. These attributes are key to the public acceptance and overall economic competitiveness of fusion energy.

Demonstration of safe operation of the fusion pilot plant is one of its most important goals. In D-T systems, tritium dominates the plant's source term, and mitigation of tritium release is key to the safety case. There is significant experience with the TFTR[3] and JET operations, and with fission power plants (particularly CANDU reactors[4]), as well as with the design of ITER,[5] that shows that tritium releases may be kept within allowable limits via design and choice of materials. All fusion concepts produce intense ionizing radiation. Neutron activation of structural materials will contribute to the source term in all fusion concepts, but again, through design, and primarily through material choice, this portion of the source term can be mitigated. The combination of source term plus pathway to release (e.g., via a large release of energy) can be minimized via design and materials choice.[6]

From an environmental perspective, minimizing waste volume and hazard overall, and avoiding greater than Class C waste as much as feasible (and completely, if possible) in the pilot plant is key. In a fusion pilot plant, greater than Class C waste can be avoided through the use of low-activation materials[7] and/or the use of alternate fuel cycles, which lowers the material activation. The pilot plant may generate some greater than Class C waste if some low-activation materials will not be fully qualified, but it should demonstrate that the FOAK fusion power plant could use these low activation materials.[8] The fusion pilot plant will generate radioactive products requiring disposal in a near-surface disposal facility, and its design should seek to generate the minimum volume of waste.

REGULATORY PROCESS

The U.S. Nuclear Regulatory Commission (NRC), an independent federal agency, regulates the Nation's civilian use of nuclear materials. This authority was granted to the NRC by Congress through the Atomic Energy Act of 1954, as amended, hereinafter referred to as the AEA.[9] In 2009, the NRC determined, "as a general matter, that the NRC has regulatory jurisdiction over commercial fusion energy devices whenever such devices are of significance to the common defense and security, or could affect the health and safety of the public."[10]

The NRC has not yet established a framework for fusion power reactors but is required to do so by December 31, 2027, per the Nuclear Energy Innovation and Modernization Act (NEIMA), which was signed into law January 16, 2019.[11] Section 103 of NEIMA requires the NRC to "complete a rulemaking to establish a technology-inclusive, regulatory framework for optional use by commercial advanced nuclear reactor applicants for new reactor license applications" by December 31, 2027. NEIMA defines an "advanced nuclear reactor" to include fusion reactors.

The NRC has begun to consider how best to regulate fusion power reactors, and on October 2, 2020, the NRC directed the staff "to consider the appropriate treatment of fusion reactor designs in our regulatory structure by developing options for Commission consideration on licensing and regulating fusion energy systems."[12] To this end, the NRC staff is evaluating three main approaches: (1) treat a fusion power reactor as a "utilization facility"; (2) regulate the use of byproduct material at a fusion facility; or (3) use a hybrid approach.[13] As a part of this process, the NRC held a public meeting October 6, 2020, jointly with DOE to discuss the regulatory framework for fusion.[14]

Utilization Facility

The term "utilization facility" is defined in the AEA to mean:

> (1) any equipment or device, except an atomic weapon, *determined by rule of the Commission* to be capable of making use of special nuclear material in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public, or peculiarly adapted for making use of atomic energy in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public; or (2) any important component part especially designed for such equipment or device *as determined by the Commission.*

The NRC has, in turn, defined "utilization facility" to specifically include nuclear fission power reactors.[15] Thus, the existing technical regulatory requirements under 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," have been tailored to nuclear fission power plants. 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," provides an alternative licensing process to Part 50 but references the detailed technical requirements of Part 50.

Although the NRC's current regulatory definition of "utilization facility" does not include fusion reactors, the broad statutory definition provided in the AEA could permit a future determination by the NRC to include fusion plants within the definition of "utilization facility." For example, in 2014, the NRC used a direct final rulemaking[16] to modify the definition of "utilization facility" to include the SHINE facility, which is an accelerator-driven subcritical device used to irradiate uranium to produce molybdenum-99 for medical purposes.[17] The decision to modify the definition of "utilization facility" and also use the 10 CFR Part 50 framework primarily stemmed from the fact that the process involved the fission of uranium atoms (a special nuclear material[18]) and the associated safety requirements such as criticality control, heat removal while operating and shutdown, and containment of radioactive fission products were determined to be applicable.[19]

Fusion power reactor designs under development do not use isotopes of uranium or fissile materials in their processes. The fuel types are isotopes of hydrogen, with lithium-containing blankets. Fusion power plants cannot have a chain reaction. As a result, safety issues associated with fusion are different from those associated with fission reactors and stem from control of relatively short-lived radioactive material, such as tritium and longer-lived radioisotopes generated by neutron activation of metallic materials in the structures.[20] If the NRC were to treat fusion reactors as "utilization facilities," it would not need to use 10 CFR Part 50. Instead, the regulatory framework could be tailored to the hazards specific to fusion through rulemaking, as further discussed in the section "Hybrid Approach," below.

Byproduct Material

In the AEA and in NRC's regulations, radioisotopes used as fuel in a fusion facility, such as tritium, or generated during the fusion process, such as tritium and activation products, are byproduct material.[21] This determination assumes the NRC would consider radioisotopes produced in a fusion reactor as being produced in an accelerator. The regulatory framework specified in 10 CFR Part 30, "Rules of General Applicability to Domestic Licensing of Byproduct Material," and 10 CFR Part 20, "Standard for Protection Against Radiation," contains the requirements that must be met when handling byproduct material as would be necessary in a fusion facility. The regulations specify requirements for environmental protection, radiation protection of workers and the public, control of liquid and gas effluents, training of staff, operating procedures and processes, decommissioning, and depending on the activity levels present, requirements for hazards analyses and emergency planning and response.

The NRC uses a risk-informed regulatory process and as such scales its regulatory requirements according to the risk posed to public health and safety from the facility and/or activity. The regulatory framework in 10 CFR Parts 20 and 30 addresses the majority, if not all, of the radiological safety issues associated with a fusion facility without the unnecessary requirements specified in 10 CFR Part 50. The NRC is able to add any requirements necessary to provide reasonable assurance of public health and safety through the rulemaking process. Use of 10 CFR Parts 20 and 30 allows Agreement States[22] to regulate the fusion devices unless the NRC determines that its authority should not be delegated to the states. Fusion devices not located in an Agreement State would be regulated by the NRC.

Right-sized regulation that ensures safety but is free from unnecessary burden is needed to enable rapid innovation in fusion technology and for fusion to be an economically viable non-carbon emission energy generation source. Provided the NRC determines that the material generated in a fusion facility can be categorized as byproduct material, the existing regulatory framework provided under 10 CFR Parts 20 and 30 is well suited to fusion technology.

Hybrid Approach

In a hybrid approach, the NRC could develop a new regulatory framework through rulemaking that uses aspects of 10 CFR Parts 20 and 30, classifies fusion facilities as "utilization facilities," and uses some aspects of 10 CFR Part 50, such as licensing of operators, if necessary. As such, the regulatory framework would be tailored to the hazards posed by fusion and would only impose regulatory requirements that the Commission deems as necessary to provide reasonable assurance of adequate protection of public health and safety and to promote the common defense and security and to protect the environment.

Finding: A regulatory process that minimizes unnecessary regulatory burden is a critical element of the nation's development of the most cost-effective fusion pilot plant.

Finding: Because existing nuclear regulatory requirements for utilization facilities (10 CFR Part 50) is tailored to fission power reactors, it is not well suited to fusion technology.

Finding: The current regulatory framework used for radiation protection and byproduct material provided under 10 CFR Parts 20 and 30 is well suited to fusion technology.

Decommissioning

Upon cessation of operations of a nuclear facility, the decommissioning process is initiated whereby the facility is radiologically decontaminated and demolished. In the process, radiologically contaminated or activated materials are packaged and shipped to a licensed disposal facility as waste. Structures and the site grounds are then remediated to ensure that any residual radioactivity remaining on the site is reduced to a point of either unrestricted or, under some circumstances, restricted use. The facility license is then terminated. Decommissioning of nuclear fission reactors has been occurring successfully and efficiently at many facilities. The NRC indicates on its website that approximately 100 material licenses are terminated each year.[23]

Finding: A fusion power reactor will need to be decommissioned due to the presence of radioactive material.

The NRC has extensive regulations that govern decommissioning of all nuclear facilities to protect the workers and the public during the entire process and until the site is released for use. To plan for decommissioning, the NRC requires that license applicants provide assurance that they will have sufficient financial resources available to complete the process.[24] In such a case, a decommissioning funding plan or a certification of financial assurance for decommissioning is required to be submitted before a license is issued. The cost of the decommissioning depends on the complexity of the process and the amount and type of waste requiring disposal and is accounted for in the decommissioning plan and in the regulatory requirements. The classification of the waste depends on the concentration and form of the materials.[25] The NRC requires that operations of a facility be conducted in a manner that minimizes contamination as a means of reducing the complexity of the decommissioning process.[26] The TFTR tokamak D-T fusion experiment was successfully decommissioned in 2002.[27] Advances in radiological decommissioning techniques are being made every year in the areas of remote tooling for segmentation and packaging of large, highly activated reactor components and likely can be applied to the future decommissioning of a fusion power reactor.[28]

Finding: Decommissioning of a fusion facility is not expected to present significant or new challenges due to the vast experience in decommissioning of materials facilities and nuclear power plants in the United States.

Most fusion designs will need to manage and dispose of tritium safely during decommissioning, which may be the most difficult issue that will need to be addressed if the tritium is mixed with long-lived isotopes in such concentrations that it is classified as greater than Class C waste.[29] These isotopes include carbon-14 and nickel-59 and niobium-94 in activated metal. High temperature treatment of the fusion components can be used to recover tritium, since it is desirable to recover the tritium for other fusion plants rather than dispose of it.

For all fusion designs, low activation metals can be used to reduce the radiological hazard to workers and decommissioning costs.[30] Currently, greater than Class C waste can only be disposed of in a high-level radioactive waste repository, which does not yet exist within the United States. The NRC is conducting rulemaking that is considering whether some concentrations of isotopes exceeding Class C limits can be safely disposed of in a low-level waste near surface disposal facility, and this rulemaking could reduce the complexity of disposal of waste containing greater than Class C waste.[31] If no repository is available and the NRC determines that the greater than Class C waste generated at a fusion facility cannot be disposed of in a low-level near surface waste facility, then prolonged storage may be necessary until a repository is available.

If the waste contains only short-lived isotopes other than Ni-63, Sr-90, and Cs-137, then it can generally be disposed of in a low-level waste near surface disposal facility, currently licensed by an Agreement State.[32,33] However, if the waste contains only short-lived isotopes including certain concentrations of Ni-63, Sr-90, or Cs-137 then it would be classified as greater than Class C waste and it may need to be stored on site for several years to allow for radioactive decay and/or blended to acceptable limits and then disposed of in a low-level waste near surface disposal facility.[34]

Finding: D-T fusion designs will need to manage, recover, and dispose of tritium safely during decommissioning. Tritium may possibly be mixed with other isotopes such that disposal in an existing low-level waste near surface disposal facility may not be possible.

Recommendation: The Nuclear Regulatory Commission should establish the regulatory framework, including the decommissioning stage, for fusion power plants as well as the pilot plant.

ECONOMIC CONSIDERATIONS

As one considers new generation pilot electrical plants and their economic value, we can look at how pilot plants have been funded in the past, their generating scale, and what has driven the economic value seen by the participants in developing these pilot plants. Table 3.2 compiles these results.

TABLE 3.2 Historic and Recent Examples of Various Pilot Generation Plants

Pilot	Type	Year	Peak Generation MWe	Cost 2020M$ /MWe	Total Cost 2020 B$	Sources/Drivers
Shippingport	Fission	1958	60	10.9	0.65	Government, private investment
Texas Clean Energy	Coal GCC	2010	377	6.4–9.3[a]	2.4–3.5	Government, private investment
Kemper County Energy	Coal+CC	2010 (2017)[b]	582	12.9[a]	7.5	Government, private investment
Callide Oxyfuel	Coal+CC	2012	30	9.1	0.27	Government, private investment
Solar PV grid scale	Solar	2005		6.7[c,d]		Cost subsidies by federal tax credit and some state tax credits. Section 1603 grants to solar companies.
Ivanpah Electric Power Plant	Solar	2013	392	6.33[d]	2.45	Federal government load guarantee, private investors
Vogtle	Fission	2020	2500	10.4	25.9	State support and federal tax incentives such as production tax credits
Dominion Energy Off-shore Pilot	Wind	2020	12	25.0[d]	0.3	State support. $300 million cost of this pilot was approved by the SCC as a result of the Virginia Transformation and Security Act of 2018.[e]
Natrium	Fission	2020	345	*>9.3*[f]	*>3.2*[f]	Government, private investment
X-Energy	Fission	2020	320	*>10.0*[f]	*>3.2*[f]	Government, private investment
NuScale	Fission	2020	720	8.5	6.1	Government, private investment

[a] Not completed.
[b] Switched to natural gas in 2017.
[c] Average price.
[d] Capacity factor of these pilots are lower than those for other baseload pilot plants noted. Solar average for early plants were between 13-19 percent, Ivanpah capacity factor 24 percent, Dominion offshore wind capacity factor 42 percent.
[e] Based on economic development for future off-shore wind plus transition to Virginia's zero carbon goal by 2045. $210 million in economic output, 900 jobs created for construction, 1,100 jobs created for operation and maintenance, $21 million in local government revenues.
[f] Based on publicly announced DOE total support of 3.2 B$ combined for the Natrium and X-energy projects with minimum 50 percent cost share from developers, and the cost split evenly between projects.

SOURCE: *Shipppingport Atomic Power Station* data from Wikipedia, https://en.wikipedia.org/w/index.php?title=Shippingport_Atomic_Power_Station&oldid=964406210;

Texas Clean Energy, *Kemper County Energy*, and *Callide Oxyfuel* data from World Nuclear Organization, https://www.world-nuclear.org/information-library/energy-and-the-environment/clean-coal-technologies.aspx;

Solar PV Grid Scale data from Lawrence Berkeley Laboratory; *Ivanpah Solar Power Facility* data from Wikipedia, https://en.wikipedia.org/w/index.php?title=Ivanpah_Solar_Power_Facility&oldid=977491449;

Vogtle Electric Generating Plant data from Wikipedia, https://en.wikipedia.org/w/index.php?title=Vogtle_Electric_Generating_Plant&oldid=964406778;

continued

Dominion Energy Offshore wind data from Hampton Roads Alliance, https://hamptonroadsalliance.com/wp-content/uploads/2020/09/Offshore-Wind-Economic-Impact-Report-092820.pdf and VA SCC ruling: Case # PUR-2018-00121, November 2, 2018;

Va. Transformation & Security Act of 2018, https://lis.virginia.gov/cgi-bin/legp604.exe?181+ful+CHAP0296+pdf;

NuScale data from https://www.sciencemag.org/news/2020/11/several-us-utilities-back-out-deal-build-novel-nuclear-power-plant; NuScale is planning to increase the power by 25 percent to 924 MWe with minor design changes without any major changes to the design. The cost per MWe and the total cost listed in this table are based on the 720 MWe design from https://newsroom.nuscalepower.com/press-releases/news-details/2020/NuScale-Power-Announces-an-Additional-25-Percent-Increase-in-NuScale-Power-Module-Output-Additional-Power-Plant-Solutions/default.aspx?utm_source=nuscalepower&utm_medium=web&utm_campaign=default-hero-1.

State, Local, and Engineering, Procurement, and Construction Support

Vertically integrated electric utilities are physically tied to the regions they serve by the large amount of infrastructure invested in their transmission and distribution network plus generation assets. These utilities have a vested interest in ensuring they respond to the desires of the populace they serve by being engaged in their communities, providing service at the level their customers require, and providing the type of generation their customers demand while they ensure reliability and resiliency. By responding to their customer base with the lowest cost of service possible while providing the services required, they obtain public support, political support and regulatory support. Unlike other industries, if they are to remain in this business sector, they cannot simply move to another state if they do not like the direction being taken by their customers, politicians, or regulators but rather must either work with them or sell their franchise to someone who does.

As a result of this relationship, state and local governments tend to work with energy providers as they know how to attract industry to increase employment and improve the quality of life for the populace that they serve with the energy they provide. Given that electricity is fundamental to modern society, the financial health of this service provider should be in the state's interest.

Looking at past pilot plants in the United States from Texas, Mississippi, California, and Virginia (Table 3.2), one can see where state plus local engagement has aided the development of these installations. The support for these facilities has come in various forms such as investment tax credits, deferment of taxes, legislative support for cost recovery up to a defined amount, and training assistance for personnel.

Finding: The economic development within a state/region helps with business attraction, retention, and growth so state and local governments work to assist industry that is located or would locate in their state to grow a new industry. Fusion has this potential.

Engineering, procurement, and construction (EPC) industries may participate as strategic partners for the building of the pilot plant if the industry participants have a relationship and there is belief that they will partner on future generation facilities.

Finding: Developers, if located in a specific state that may increase employment with the deployment and use of fusion technology, could participate in state incentives or federal incentives and could see strategic value in participating with the fusion pilot plant.

Federal Support

Federal support of pilot plants of any new advanced electricity generation technology is important. A recent example is the October 2020 announcement of federal support for advanced fission concepts (Table 3.2). A fusion pilot plant provides a number of potential national security benefits, including increased scientific knowledge that can support other advanced applications for the nation; sustainability of fuel supply; enhancing the diversity of firm energy sources for the future with the potential to assist with the restoration of the transmission system; and development of a new industry to provide economic value to the nation as a provider of materials, engineering, and facilities to other countries.

As has been seen in other projects, the federal government has been actively engaged in cost sharing.[35] Fusion should be considered as a payment-for-milestones as described in the recently enacted bill HR-133 Sec. 2008. Other types of cost sharing include tax incentives such as federal tax credits, production tax credits, grants to specific companies, enhanced rates of return for utility investments, and R&D investment through universities and National Laboratories.

Finding: Federal support of pilot plants featuring a new generating technology like fusion is common and will be critical for fusion.

Generation Size and Cost

The cost of new technology pilot plants has varied over the years and with the generating technology. Not surprisingly generating costs of pilot plants are typically above those for mature plants. Table 3.2 gives a snapshot of pilot generation projects, along with some of their costs to construct reported in 2020 dollars per MW. These examples help provide the proper context for a fusion pilot plant whose goal is to accelerate the development of a FOAK fusion power plant. Indeed, it is this stated goal of a pilot that differentiates it from fusion devices designed to address purely technical or scientific challenges. Figure 3.4 shows, for recent examples

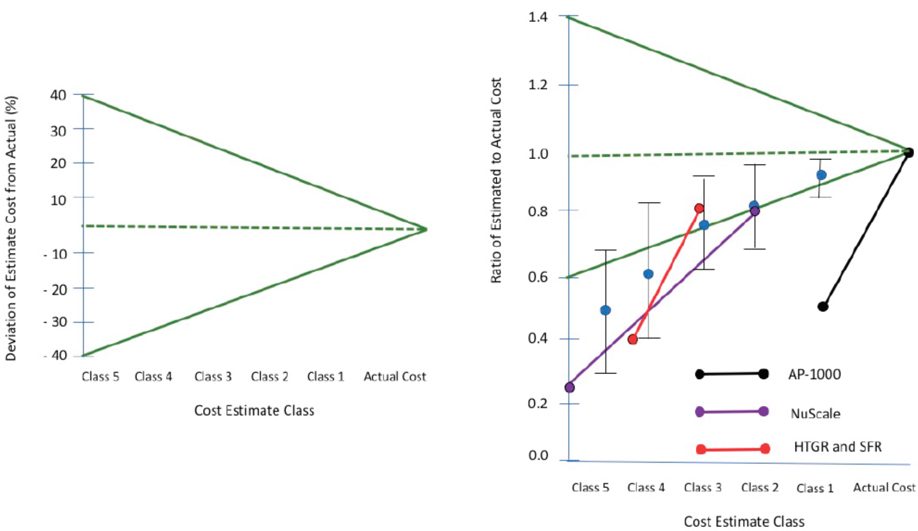

FIGURE 3.4 Cost uncertainty for different levels of design maturity, based on the Association for the Advancement of Cost Engineering International and the Electric Power Research Institute methodology for recent large fission energy projects. As designs mature (Class 5 → Class 1), the cost uncertainty decreases (*left*) but the actual cost increases (*right*). This trend was consistent across different generation technologies. SOURCE: MIT Energy Initiative, 2018, *The Future of Nuclear Energy in a Carbon Constrained World: An Interdisciplinary MIT Study*, https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/. Copyright © 2018 Massachusetts Institute of Technology.

from fission, that as the maturity and completeness of the design concept increases the absolute costs generally tend to increase. This example clearly illustrates the importance of developing a mature design to develop a reliable cost and schedule basis, and obviously motivates one to minimize the pilot's scale and cost while still meeting its technical requirements.

The first consideration is total cost. The ability of individual investors and utilities to invest in a pilot plant and/or FOAK power plant depends on the overall cost estimate for the pilot facility. Their investment will likely be based on the overall capital cost of the pilot facility and the firm's capitalization capacity or risk investment capability. Input to the committee indicated that only the largest U.S. utilities have capitalization capacity that would allow ~$5 billion investments in a known technology, and many utilities would be more limited than this in their total cost. An exception to this in Table 3.2 is Vogtle at more than $25 billion cost. Vogtle uses well-established fission technology so is not a pilot in that sense but is listed because it was the first major fission build in a generation in the United States with a depreciated life expectancy of 40 years. It continues to face challenges even with substantial government backing, and its cost escalations provide a cautionary tale about large size and total costs. Conversely, smaller investments will motivate utilities to purchase the technology, while larger costs can risk the viability of the entire utility. This immediately suggests a similar limit, effectively set by the U.S. electrical marketplace, for a FOAK fusion power plant that even following a fusion pilot will be a relatively immature technology. The maximum FOAK cost should be evaluated periodically based on input from the energy marketplace, consistent with the final recommendation of Chapter 2.

> **Finding**: On the basis of today's energy market and costs, the FOAK fusion power plant will need to have a total overnight construction cost less than \$5 billion to \$6 billion in order to be viable in the present U.S. electrical marketplace with a projected operation life of at least 40 years for the plant.

Given this reality of the U.S. market, the next consideration is the total cost for the fusion pilot plant. The pilot plant has linked technical and economic goals with significant private-sector contributions. The private-sector developers must in turn follow the constraints of the marketplace in which they will deploy their technologies in order to attract investment. If the private sector, even with government backing (Table 3.2), will not accept a total price past \$5 billion to \$6 billion for generating technology already demonstrated at scale, then it will certainly not accept this for the pilot plant. In addition, a pilot plant should have long term benefit to the industry's development so the capital cost can be depreciated over a long period of time.

A pilot plant does not need to generate power at the same level of a FOAK fusion power plant or NOAK power plant, which would be determined by economies of scale and marketplace demands for a mature energy technology. The pilot plant will not be designed to demonstrate the normalized generation construction costs, \$/MW, of a FOAK fusion power plant for several reasons. The first is that the technology readiness is less mature, which is the motivation for building a pilot plant. Compared with other technologies such as fission, solar power, and off-shore wind generation, fusion is at a lower level of technological readiness. The fusion pilot plant will improve technological readiness. The second is that there are economies of scale that can be realized by designing and operating the plant at higher electrical powers. These can be realized by making the plant larger on the basis of the same scientific and technological basis but will increase the cost. This is in conflict with the goal of seeking to build the pilot plant at the lowest possible cost. An example of a relatively low power pilot plant is the Dominion Energy Off-shore Wind pilot at 12 MWe. The normalized cost was relatively high at \$25 million per MWe. The higher normalized cost should be expected at low power because some costs (permitting, design) are relatively insensitive to scale and represent a minimum cost. Nonetheless, there is a strong motivation to reduce the normalized generation costs,

$/MW, even for the fusion pilot plant. This is because it reduces the extrapolation to the marketplace. It will provide both the developers and utility operators greater assurance in committing to a FOAK fusion power plant. Projections of the normalized cost for a FOAK commercial plant will be a significant consideration at the decision point to construct the pilot plant, discussed in Chapter 5. Hence, this metric should be considered during the design phase of the pilot plant. Due to the changing marketplace, engaging experts in the electrical industry at the time of this decision would be valuable.

The levelized cost of energy (LCOE) for the FOAK fusion power plant will be defined in large part by the normalized generation construction costs, facility availability, and the operation and maintenance costs. Operating the pilot plant into a third phase represents an opportunity to improve our knowledge of mean time to failure for components, better defining the operating lifetime in the complex fusion environment and potentially testing advanced materials. It is important to note this benefit gained from use of the pilot plant must be balanced against the additional costs associated with Phase 3 operations. The operating and maintenance phase of the pilot plant will provide valuable data to estimate the operating and maintenance costs of the FOAK fusion power plant. While increased normalized costs are to be expected in the pilot plant due to the low technological maturity, developing an integrated solution that reduces the operating and maintenance costs and demonstrating it on the pilot plant would be advantageous. This has implications for the design of the in-vessel components, including the blanket, and remote maintenance.

Conclusion: A fusion pilot plant should have a generating power >50 MWe and total overnight construction cost of less than $5 billion to $6 billion.

This conclusion indicates a maximum normalized cost 100M$ per MW, which is more than four times larger than the examples cited in Table 3.2. Such a high normalized cost for the pilot plant would unlikely be sufficient to motivate funding for a FOAK fusion power plant. This motivates design efforts to decrease the normalized cost of the pilot plant and/or provide a clear pathway to reduce normalized cost through scale or parallel technology improvements.

Siting is another important factor in cost. One would have to assume that due to the technical challenges associated with fusion technology, the cost to build a pilot plant would be similar to those of advanced firm generating plant pilots or the offshore wind pilot. If possible, as much balance of plant that could be repurposed from an existing generator facility that is being retired, but was properly maintained, could reduce the balance of plant expenses. Otherwise, the pilot plant should use a standardized balance of plant design that fits the overall balance of plant parameters and enables operation of the smallest plant capable of meeting the performance criteria. The overall cost requirement on a pilot facility could also be reduced if the plant is sited near a utility location with synchronous condensers, storage, or standby generators, since these features are required to support a fusion pilot plant. The present cost risk for fusion is the thermal side of the plant, not the balance of plant, so the value should be considered based on the cost of the thermal side of the plant and using the minimum cost balance of plant design to provide electrical energy. The balance of plant could have a cost profile as large as the thermal fusion core, and therefore this is an important consideration for a fusion pilot to meet its cost goals.

> **Finding**: For improved economics, the fusion pilot plant should take advantage of siting at locations where previous generation plants have been installed to reduce electric transmission or substation infrastructure expenses or be located at a government facility with excess electrical generation and load capacity to support its function.

NOTES

1. See, for example, J.E. Menard, T. Brown, L. El-Guebaly, M. Boyer, J. Canik, B. Colling, R. Raman, et al., 2016, Fusion nuclear science facilities and pilot plants based on the spherical tokamak, *Nuclear Fusion* 56:106023, https://doi.org/10.1088/0029-5515/56/10/106023.
2. See, for example, B. N. Sorbom, J. Ball, T. R. Palmer, F. J. Mangiarotti, J. M. Sierchio, P. Bonoli, C. Kasten, et al., 2015, ARC: A compact high-field fusion nuclear science facility and demonstration power plant with demountable magnets. *Fusion Engineering and Design* 100:378, https://doi.org/10.1016/j.fusengdes.2015.07.008.; M. LaBerge, 2007, An acoustically driven magnetized target fusion reactor, *Journal of Fusion Energy* 27:65, https://doi.org/10.1007/s10894-007-9091-4.
3. C. A. Gentile, S. Raftopoulous, P. LaMarche, M. Viola, T. Walters, M. Kalish, T. Kozub, et al., 1996, TFTR tritium operations lessons learned, *Fusion Technology* 30:1564-1566, https://doi.org/10.13182/FST96-A11963173.
4. Canadian Nuclear Safety Commission, December 2009, "Tritium Releases and Dose Consequences in Canada in 2006", INFO-0793, https://nuclearsafety.gc.ca/pubs_catalogue/uploads/CNSC_Release_and_Dose_eng_rev2.pdf.
5. I. R. Cristescu, I. Cristescu, L. Doerr, M. Gulga, and D. Murdoch, 2007, Tritium inventories and tritium safety design principles for the fuel cycle of ITER, *Nuclear Fusion* 47(7):S458, https://doi.org/10.1088/0029-5515/47/7/S08.
6. M. Victoria, N. Baluc, and P. Spätig, 2001, Structural materials for fusion reactors, *Nuclear Fusion*, 41(8):1047, https://doi.org/10.1088/0029-5515/41/8/308.
7. D. A. Petti, K. A. McCarthy, N. P. Taylor, C. B. A. Forthy, and R. A. Forrest, 2000, Re-evaluation of the use of low activation materials in waste management strategies for fusion, *Fusion Engineering and Design* 51-52:435-444, https://doi.org/10.1016/S0920-3796(00)00229-5.
8. L. El-Guebaly, L. Mynsberge, C. D'Angelo, A. Rowcliffe, B. Pint, and ARIES-ACT TEAM, 2017, Design and evaluation of nuclear system for ARIES-ACT2 power plant with DCLL blanket, *Fusion Science and Technology* 72:17-40, https://doi.org/10.1080/15361055.2016.1273669.
9. Atomic Energy Act of 1954 (P.L. 83-703).

10. SRM-SECY-09-0064, "Regulation of Fusion-Based Generation Devices" (Apr. 20, 2009) (SECY-09-0064).
11. U.S. Senate Committee on Environment and Public Works, "Nuclear Energy Innovation and Modernization Act (NEIMA)," https://www.epw.senate.gov/public/index.cfm/neima, updated January 28, 2019.
12. SRM-SECY-20-0032, "Rulemaking Plan on Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors (October 2, 20202) (SECY-20-0032).
13. W. Reckley, 2020, "Thoughts on NRC Regulatory Approach for Fusion," presented at the DOE/NRC/FIA Public Forum on a Regulatory Framework for Fusion, updated October 6, 2020. https://science.osti.gov/fes/Community-Resources/Workshop-Reports/DOE-NRC-FIA-Public-Forum.
14. W. Reckley, 2020, "Thoughts on NRC Regulatory Approach for Fusion," presented at the DOE/NRC/FIA Public Forum on a Regulatory Framework for Fusion, updated October 6, 2020. https://science.osti.gov/fes/Community-Resources/Workshop-Reports/DOE-NRC-FIA-Public-Forum.
15. C.F.R. 50.2 (definitions of "utilization facility" and "nuclear reactor").
16. Definition of Utilization Facility, Direct Final Rule, 79 Fed. Reg. 62,329 (Oct. 17, 2014).
17. SHINE Preliminary Safety Analysis Report, Chapter 4—Irradiation Unit and Radioisotope Production Facility Description dated May 31, 2013 (ADAMS Accession No. ML13172A265).
18. Title I of the Atomic Energy Act of 1954 defines "special nuclear material" as plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235.
19. SECY-14-0061, "Direct Final Rule: Adding Shine Medical Technologies, Inc., Accelerator-Driven Subcritical Operating Assembly to the Definition of Utilization Facility"(June 16, 20).
20. S. Sandri, G. M. Contessa, M. D'Arienzo, M. Guardati, M. Guarracino, C. Poggi, and R. Villari, 2019, A review of radioactive wastes production and potential environmental releases at experimental nuclear fusion facilities, *Environments* 7(1):1-12, https://doi.org/10.3390/environments7010006.
21. See 10 C.F.R. § 30.4 (definition of "byproduct material").
22. United States Nuclear Regulatory Commission, "Agreement State Program," https://www.nrc.gov/about-nrc/state-tribal/agreement-states.html, updated January 13, 2021.
23. United States Nuclear Regulatory Commission, "Decommissioning of Nuclear Facilities," https://www.nrc.gov/waste/decommissioning.html, updated August 26, 2020.
24. See 10 C.F.R. 50.75, "Reporting and recordkeeping for decommissioning planning," and 10 C.F.R. 30.35, "Financial assurance and recordkeeping for decommissioning."
25. See 10 CFR 61.55, "Waste classification."
26. 10 CFR 20.1406(c), the NRC requires all licensees to minimize the introduction of radiological contamination into the site environment to keep doses to as low as reasonably achievable and to facilitate decommissioning.
27. E. Perry, J. Chrzanowski, C. Gentile, R. Parsells, K. Rule, R. Strykowsky, and M. Viola, 2003, "Decommissioning of the Tokamak Fusion Test Reactor," presented at the 20th IEEE/NPSS Symposium on Fusion Engineering, https://doi.org/10.1109/FUSION.2003.1426633.
28. D. Stenger, A. C. Roma, and S. S. Desai, July 2019, "Innovation in decommissioning and their application abroad," *Nuclear News,* https://www.hoganlovells.com/~/media/hogan-lovells/pdf/2019/2019_08_16_jul19nn-innovation-reprint.pdf?la=en. Pp. 45-52.
29. See 10 CFR 61.55, "Waste classification."

30. S. Sandri, G. M. Contessa, M. D'Arienzo, M. Guardati, M. Guarracino, C. Poggi, and R Villari, 2019, A review of radioactive wastes production and potential environmental releases at experimental nuclear fusion facilities, *Environments* 7(1):1-12, https://doi.org/10.3390/environments7010006.
31. D. Stenger, A. C. Roma, amd S. S. Desai, July 2019, Innovation in decommissioning and their application abroad, *Nuclear News,* https://www.hoganlovells.com/~/media/hogan-lovells/pdf/2019/2019_08_16_jul19nn-innovation-reprint.pdf?la=en. Pp. 45-52.
32. See 10 C.F.R. 30.4 (definition of "byproduct material").
33. United States Nuclear Regulatory Commission, "Agreement State Program," https://www.nrc.gov/about-nrc/state-tribal/agreement-states.html, updated January 13, 2021. United States Nuclear Regulatory Commission, "Decommissioning of Nuclear Facilities," https://www.nrc.gov/waste/decommissioning.html, updated August 26, 2020.
34 See 10 CFR 61.55, "Waste classification."
35. Office of Nuclear Energy, 2020, "It's Time for the United States to Demonstrated Advanced Reactors," https://www.energy.gov/ne/articles/it-s-time-united-states-demonstrate-advanced-reactors-0.

4

Innovations and Research Needed to Address Key Fusion Pilot Plant Goals

It is clear that significant enthusiasm exists in the fusion community toward the proposed U.S. strategy of developing, designing, and building a compact fusion pilot plant, which would carve out a unique niche in the worldwide pursuit of fusion energy involving smaller physical size, lower power output, and lower capital cost. This enthusiasm is manifest in the recent fusion community planning process[1] and the numerous private startup companies that have garnered significant investment and are working to further the development of numerous fusion confinement and potential power plant concepts. However, research aimed at developing a fusion-based power plant has, to date, focused mainly on the plasma physics and confinement itself, including the plasma, the divertor and first wall, as well as the magnets and heating systems. It is obvious that substantial innovations will be required prior to completing a detailed engineering design and site selection leading to a decision to begin construction. This is necessary since private- and public-sector funding for fusion materials and technology, and corresponding research activities, have been substantially lower than for fusion confinement concepts.

The desire to put fusion power on the grid in a pilot plant requires a significant investment into the R&D of materials and fusion nuclear technology to increase the technical readiness to a level that enables a pilot plant. The attractiveness of a fusion system, in terms of economics, safety, and environmental considerations, is mainly determined by the materials and design of systems that will extract the fusion power and convert it to electricity and sustainably close the fuel cycle, which in the case of a deuterium-tritium (D-T)-based reactor design includes the generation, or breeding, of tritium. At present, these systems for the divertor and first wall armor plasma-facing components (PFCs), and integrated blanket are at a very low technology readiness level (TRL), and thus require substantial R&D. However, as noted in the Fusion Energy Sciences Advisory Committee report on Transformative Enabling Capability for Efficient Advance Toward Fusion Energy,[2] numerous recent advances in advanced materials and manufacturing, high-temperature and/or high-field magnets, and tritium processing offer the potential to significantly increase the TRL to enable construction and mitigate risks towards the initial operation of a compact pilot plant.

The divertor, first wall, and blanket systems for operation in a fusion power reactor represent a significant materials development challenge resulting from the neutron-induced degradation, thermal mechanical loading, and corrosive environment. The operating environment envisioned for the materials-structures for fusion energy far exceed those of current technology, including light water reactors that are impacted by many materials degradation problems and expected in ITER as shown in Figure 4.1.[3,4,5,6] Figure 4.1 shows a schematic view of ITER in addition to calculations of the lifetime neutron fluence expected for ITER components compared to the *annual* neutron fluence anticipated in the European DEMO reactor,[7]

ITER Lifetime Neutron Fluence (n/m^2; E>0.1 MeV)	Compact Fusion Pilot Plant Annual Neutron Fluence (n/m^2; E>0.1 MeV)	Component
$4x10^{25}$	$2x10^{26}$	Blanket
$5x10^{18}$	$3x10^{21}$	Magnet
$2x10^{25}$	$8x10^{25}$	Divertor
$1x10^{23}$	$2x10^{26}$	Vacuum Vessel

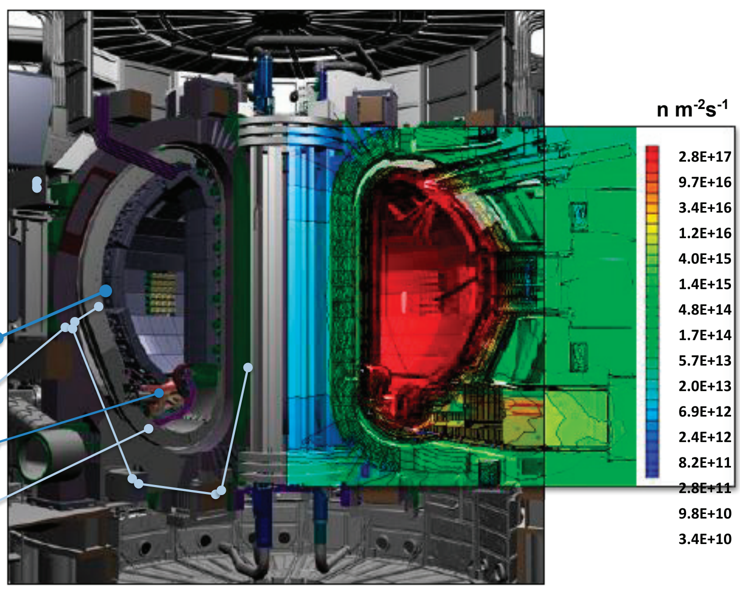

FIGURE 4.1 Overview of neutronics calculation of (a) neutron fluence to components in ITER over the operation lifetime and in 1 year of operation of a European DEMO reactor, (b) showing the position dependent neutron flux. SOURCE: Republished with permission of Annual Reviews, Inc., from S.J. Zinkle and L.L. Snead, 2014, Designing radiation resistance in materials for fusion energy, *Annual Review of Materials Research* 44:241-267; permission conveyed through Copyright Clearance Center, Inc.

and demonstrates that a demonstration reactor or pilot plant will experience neutron fluences and degradation significantly greater than ITER. To date, numerous designs have been proposed for fusion blankets to breed tritium; however, all such concepts are at a low TRL. An integrated strategy is needed to develop and test the integrated first wall and breeding blanket concepts in time for readiness for deployment of a compact fusion pilot plant.

There are two inter-related motivations for innovations and research in fusion energy. The first is to ensure that the key goals identified in Chapter 3 are met. The second is to use innovations to reduce the cost of the pilot plant and improve the economics of a first-of-a-kind (FOAK) power plant. The required innovations involve scientific and technical advancements, described below in the section "Scientific and Technical Innovations and Research Advances," in order to demonstrate the required performance of the fusion confinement concept, extract the fusion power, and sustain the fusion fuel cycle. The sections "Participants in Developing a Pilot Plant" and "Models for Public-Private Partnerships" discuss the opportunities for public-private partnerships, given the success of such technology development partnerships including the NASA Commercial Orbital Transportation Services program, and options for defining the private-sector and federal government development priorities.

Recommendation: To meet the challenge of having a viable design by 2028 and initial pilot plant operation in 2035-2040, innovations in fusion confinement concepts and technology to extract fusion power and close the fusion fuel cycle should be developed in parallel. This will enable the engineering design of a pilot plant and the construction decisions to be accelerated by a combination of government and private funding.

SCIENTIFIC AND TECHNICAL INNOVATIONS AND RESEARCH ADVANCES

Virtually every major component of a future nuclear fusion energy reactor, except for structural materials made of reduced activation ferritic-martensitic alloys, will require materials development in order to provide confidence in the ability to withstand significant limits of essential material properties including neutron damage, creep resistance, fracture toughness, surface erosion/re-deposition, corrosion, chemistry, thermal conductivity, and many others. Further, a particular challenge is the need to safely and efficiently close the fuel cycle, which for deuterium-tritium fusion designs involves the development of blankets to breed and extract tritium, as well as the fueling, exhausting, confining, extracting, and separating tritium in significant quantities.[8] Although this is often put off for the future, the goal of economical fusion energy within the next several decades as a U.S. strategic interest[9] drives the need to rapidly increase the research and development of enabling materials, components, and fusion nuclear technologies. Some of the capabilities needed for development and testing are straightforward and could be prepared in the short term, but a full research program will require test facilities producing environments increasingly similar to a fusion power plant to assess reactor-relevant power exhaust handling in the fusion neutron environment.

In the 2019 report *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*[10] (hereafter the "*Burning Plasma* report"), the higher magnetic field made possible by the development of high temperature superconducting (HTS) magnets was identified as a key enabling technology that provides a potential path, when combined with advanced operating scenarios, to a compact fusion pilot plant with high fusion power density, and high poloidal beta enabling high bootstrap current fraction. Input to the committee stated that there are numerous other fusion confinement concepts that may provide a pathway to electricity generation.

Integrated simulation has long been an important part of fusion energy research, with many recent examples of increasing physical fidelity in the *Burning Plasma* report. Advancement of the conceptual fusion pilot plant design(s) toward a construction decision will benefit from modeling and simulation incorporating multiple physics and multiscale phenomena with increasing fidelity into simulations to evaluate and refine design options. High-fidelity simulation capability, validated by experiments, will continue to benefit from the emergence of exascale computing platforms, and can be employed both directly, and to facilitate development of reduced models, including via artificial intelligence. Physics, system, and process models can be combined into comprehensive full device models, which will likely contribute to evaluating the operations and maintenance of the pilot plant. Likewise, the incorporation of best practices and lessons learned from large-scale project construction and system integration, including from ITER and recent nuclear fission power plants, in order to perform engineering computer aided design, structural analysis, and process and control modeling will provide an important opportunity to optimize the design and integration of the fusion pilot plant. Such computational modeling and analysis will increase confidence in the operation and reliability of complex pilot plant components, including the divertor and PFCs, structural materials for the vacuum vessel, shielding and blanket modules, as well as functional and diagnostic materials that operate under severe thermal-mechanical, corrosion, and radiation environments.

It is also important to note that meeting the aggressive development timeline of putting a FOAK fusion power plant on the electrical grid by 2050 will require rapid development of new programs and facilities to accelerate the scientific and technical innovation needed to finalize the engineering design of the fusion pilot plant.

Fusion Performance and Plasma Confinement

Producing significant net electric power from fusion requires achieving temperatures and pressures sufficient for high fusion power density, along with energy confinement times necessary to sustain those conditions with minimal auxiliary power. A high duty factor must be maintained for long periods of time, up to several months in the latter stages of pilot plant operation to meet the availability goals of a pilot plant.

To achieve practical applications to replace present electrical generating processes with fusion will require substantial progress in producing, maintaining, and heating of a burning plasma, while keeping it confined without damaging the engineered systems surrounding the plasma. Fusion performance can be characterized by the fusion energy gain, or the closely related triple product of ion density, ion temperature, and energy confinement time. For D-T devices operating near the optimal temperature of 8-20 keV, a triple product of roughly 4–10 (in units of 10^{21} keV s m^{-3}) is required to achieve the high fusion gain needed for net electricity production. Previous experiments on the JET, JT-60U, TFTR, and DIII-D tokamaks have achieved peak triple products of roughly 1, and sustained values of approximately 0.2 for several seconds, as shown in Figure 4.2. Stellarator experiments on W7-X and Large Helical Device (LHD) have achieved peak values of roughly 0.1, and LHD has sustained lower performing plasmas for more than 1,000 seconds. Other magnetic fusion concepts, such as the field reversed configuration, have made rapid progress but remain orders of magnitude behind the triple product values achieved in tokamaks and stellarators. A combination of significant innovations enabling concept improvement, and incorporating technological advancements, such as HTS magnets, is needed to achieve conditions for high gain and long-duration or high repetition rate for pulsed systems at a scale that is potentially relevant for cost-effective fusion power production.

Finding: Significant progress is needed in fusion plasma confinement to demonstrate uninterrupted operation of a burning plasma in a high-performance confinement concept.

Conclusion: Before proceeding to the final pilot plant design phase, a deuterium-tritium (D-T) fusion concept should simultaneously demonstrate temperatures of at least 100 million degrees C and a triple product greater than 2 (in units of 10^{21} keV s m^{-3}), corresponding to a D-T equivalent plasma energy gain >1.

Conclusion: For alternate fuels, equivalent parameters needed for net plasma energy gain must be demonstrated.

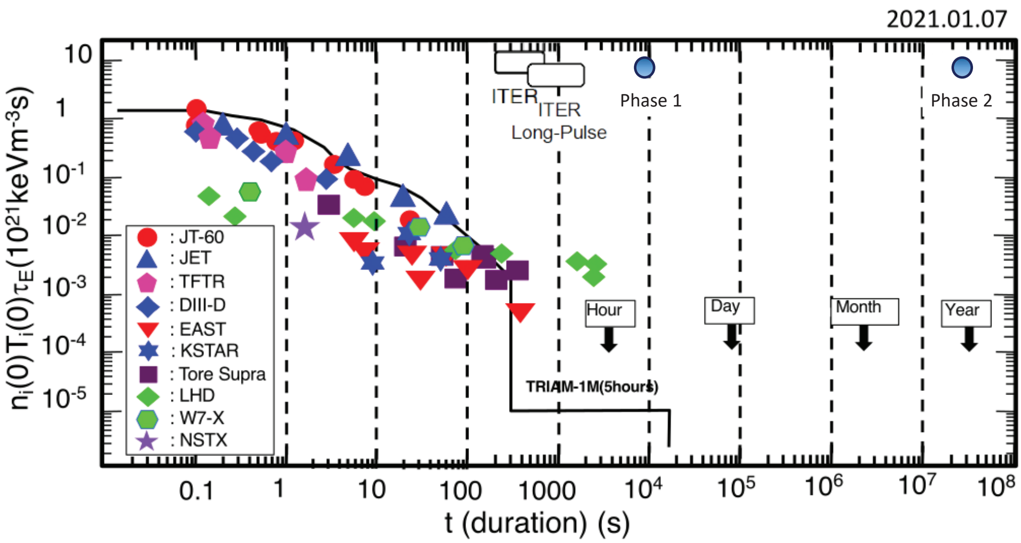

FIGURE 4.2 Diagram of fusion plasma performance versus duration of plasma operation shows the fusion triple product versus duration, with the product $n_i(0)\tau_E T_i(0)$ proportional to fusion energy gain. The highest performance is achieved for short duration. The longest plasma duration is achieved with superconducting magnets with sustained injection of external plasma heating power. TRIAM-1M (Japan) has the world record in plasma sustainment of 5 h and 16 minutes. Tore Supra (France) was sustained for more than 5 minutes, and the plasma was sustained in the superconducting Large Helical Device (LHD) in Japan for 48 minutes. NOTE: See M. Kikuchi and M. Azumi, 2015, *Frontiers in Fusion Research II: Introduction to Modern Tokamak Physics*, Springer International Publishing, Switzerland. SOURCE: Courtesy of M. Kikuchi.

Conclusion: For long pulse and sustained concepts, the values of plasma energy gain should be sustained for at least several characteristic plasma times including energy confinement times.

The specific innovations required to advance a concept toward readiness for a pilot plant vary significantly with the characteristics of the concept. For brevity and concreteness, the remainder of this subsection focuses on the tokamak, as it is closest to readiness in terms of triple product, and was identified as the leading magnetic fusion concept in the 2019 *Burning Plasma* report. The following considerations would have to be modified for other fusion concepts and fusion fuels.

In a tokamak, the toroidal component of the magnetic field is produced by external coils, which will need to be superconducting in a pilot plant, to avoid the resistive losses associated with copper coils. The other component of the confining magnetic field, the poloidal field, is produced by current that flows in the plasma itself. In a pulsed tokamak, this current can be driven via an external solenoid.

However, if the tokamak is to operate continuously, the current must be driven by other means. A number of technologies can be applied, but will require substantial additional development, as discussed below on innovations needed for plasma heating and actuators. If the tokamak can be operated at a high value of the poloidal beta (the ratio of plasma pressure to the pressure associated with the poloidal field), it can produce a substantial fraction of the needed current via the self-driven "bootstrap" current. The larger the fraction of the current that is self-driven, the less need there is for external current drive and its associated recirculating power.

Fusion performance of a sustained tokamak can then be characterized by three key performance metrics: (1) the fusion triple product, or fusion gain, which must be large enough for the plasma to produce net electricity and be predominantly self-heated by fusion products (i.e., "burning plasma"), (2) the pressure, which determines fusion power density, and (3) the bootstrap current fraction, which must be high in order to avoid large recirculating power, which reduces net electric power, and enhances the heat load on material surfaces. Simultaneous optimization of (1), (2), and (3) requires both advanced technology, such as HTS magnets for high magnetic field, and advanced physics, to simultaneously reach high normalized performance via optimization of design parameters such as plasma shape and aspect ratio, as well as fueling and control actuators. In addition, fast particles must be well confined, and transients such as disruptions and edge localized modes must be avoided or strongly mitigated.

Finding: Projecting regimes with confidence requires the development of theory and modeling tools, carefully validated against experiments, that are capable of predicting all the important aspects of plasma behavior, using both reduced models and integrated simulations spanning alpha-particle physics, transport and confinement, stability, boundary layer physics, and plasma material interactions.

Finding: All fusion concepts require significant innovations to address issues going beyond simple fusion performance metrics. Key integration issues include confinement of charged fusion products, exhaust of heat and helium ash, avoidance or strong mitigation of transient events, and integration of a hot fusion core with a boundary region compatible with exhaust requirements and long-term survival of plasma-facing materials.

Recommendation: As fusion concepts approach performance metrics required for a pilot plant, the Department of Energy should support innovative facilities capable of solving key integration physics issues including core-edge integration of a high fusion performance core with a boundary consistent with long-term survival of plasma-facing materials and exhaust

of heat and helium ash. Support should incorporate extensive model and diagnostic development, and model validation.

High Heat Flux Challenge for Plasma-Facing and First Wall Components

Power exhaust in high power density, compact fusion systems has two key challenges. One is the experimentally observed narrow steady-state e-folding length of power flow in the scrape-off-layer (SOL). Since the peak heat flux at the divertor plate (q_{div}) is inversely proportional to the power e-folding length (λ_q), narrow power e-folding length gives rise to an excessive heat flux at the divertor plate. Experimental observation shows $\lambda_q \sim 1/B_p$[11,12] where λ_q and B_p are power e-folding length and the poloidal field at the plasma surface. Since $B_p \sim I_p/a_p$, power e-folding length in a compact fusion device tends to be smaller. However, the high operating density of a compact fusion device is likely beneficial for enhancing radiative cooling and to achieve detached plasma state.

Another challenge is taming the transient heat flux including those due to edge localized modes (ELMs). ELMs are an edge relaxation phenomena driven by the peeling/ballooning mode, whose onset is reasonably well understood and characterized.[13] ELM suppression by methods such as application of 3D magnetic perturbations in DIII-D[14] reveals the promise for minimizing the impact of transient heat fluxes on the first wall, but much more research is required, especially for managing the heat flux challenge of a compact, high power density fusion reactor.

Finding: High plasma core power density presents a significant heat exhaust challenge for the PFCs, armor, and first wall in fusion systems.

Intensive experimental and theoretical research within the past several years has focused on the analysis and testing of advanced divertor configurations such as the Snowflake (SF) divertor,[15] super X (SX) divertor,[16] and Small-Angle Slot (SAS) divertor.[17] Further, as discussed by Menard and co-workers,[18] the recent low aspect ratio HTS FNSF/Pilot plant design successfully showed that the long-leg/SX divertor can be implemented for the outboard divertor leg in a compact fusion system. As well, the SAS divertor tested in DIII-D has successfully demonstrated stable diverter detachment with a compact divertor geometry and indicates that a slot with a V-shaped corner is promising for a reactor.[19]

Finding: Solutions are required to enable operation of controllable, dissipative boundary plasma conditions in magnetic toroidal devices, in addition to developing predictive understanding of divertor heat loads and methods to accommodate or avoid transient heat loading and transport and material migration in the plasma boundary/scrape off layer. Further, such solutions are necessary to develop the requirements for in-vessel components such as plasma heating systems, PFCs, and first wall armor.

Recommendation: The Department of Energy should support studies of the compatibility of innovative divertor designs in toroidal confinement concepts with divertor plasma detachment, which can significantly relax the radiated power requirement, and include the possibility of liquid metal plasma-facing components.

Recommendation: The Department of Energy should support a research program and new facilities, including linear devices for testing plasma-facing components (PFCs) and non-plasma heat flux testing platforms, to identify, evaluate, and finalize a high-confidence, robust design for PFC and first wall armor materials, including both solid and liquid metal options, that are compatible with managing steady state and transient power loading.

High-Temperature Superconducting Magnets

It has been known for many decades that access to high magnetic fields is an important requirement for the achievement of magnetic fusion energy. Furthermore, for virtually all magnetic fusion concepts, the fields must be generated by superconducting magnets. In general, the highest magnetic fields achievable in practical large-scale superconducting magnets have been limited by the properties of the superconducting materials themselves. The two main well-established options are niobium-titanium (NbTi) and niobium-tin (Nb_3Sn) with corresponding maximum fields approximately 7 T and 12 T, respectively. In recent years, industry has developed two new classes of superconducting materials for large-scale applications, with far superior properties[20,21,22]—namely, rare-earth barium copper-oxides (REBCO) and bismuth-strontium calcium copper-oxides (BSCCO). The fields and current densities are both much higher than for NbTi and Nb_3Sn.

REBCO is a recently developed superconductor applicable to large-scale practical applications, with YBCO (yttrium-barium copper-oxide) a leading contender for fusion.[20] YBCO superconductors typically have the form of a tape consisting of multiple deposition layers. YBCO tapes have superior electrical and mechanical properties compared to Nb_3Sn, leading to significant interest and private investment within the fusion community. The main disadvantages of YBCO superconducting tapes are their high cost and the fact that it has yet to be demonstrated that they can actually be wound into large-scale coils, although substantial efforts utilizing both private and public funding are under way to demonstrate the performance of such high temperature superconducting (HTS) magnets, as well as efforts on insulators and stabilizers. However, it is important to build upon this recent investment to continue the development of HTS magnets, as well as to better understand the response of HTS magnets to 14 MeV neutron irradiation.

Finding: The demonstration of sustained performance of HTS magnets at high field strength, including the avoidance or mitigation of magnet quench with required structural strength/load response, is required to contribute technological advances to multiple fusion confinement concepts.

Recommendation: The Department of Energy should support a research program, including a facility for cryogenic neutron testing, to define neutron degradation limits on HTS magnets and/or optimize neutron shielding of magnets and to demonstrate mechanical design, magnet performance, and degradation limits of HTS magnets that impact multiple fusion concepts.

Structural and Function Materials for First Wall and Vacuum Vessel Components

The scientific understanding of the neutron-induced degradation of reduced activation ferritic martensitic (RAFM) alloys provides confidence up to a dose of 50 dpa/500 appm He (~5 MW-year m^{-2}) within the temperature range from approximately 400 to 550°C, as shown in Figure 4.3.[23,24] Figure 4.3a demonstrates the substantially lower volumetric swelling of RAFM, while Figure 4.3b shows the evolution of yield strength with temperature and dose, indicating that the yield strength and hence work hardening is not changing above 450°C.[25] Figure 4.4 demonstrates that the radiation embrittlement is generally manageable up to a helium concentration above 500 atomic parts per million (appm),[26] that corresponds to a neutron wall loading of ~5 MW-year m^{-2}. This provides confidence in RAFM structural materials for use in a fusion pilot plant, although the degradation service limit above this fluence is not yet established.

However, RAFM materials have not been fully demonstrated in the complex environmental loading conditions of a fusion pilot plant, which include multiple combined degradation modes including neutron degradation, He and H_2 gas generation from nuclear transmutation, injected ions and permeating tritium, significant and potentially time-varying heat flux, complex mechanical loading, and magnetic fields and corrosive coolants, including the effects of radiolysis. Materials development efforts must focus on meeting all the requirements of a recognized code standard. Experience gained with licensing the structural materials of the cryostat, first wall armor, and vacuum vessel of ITER can be applied to the fusion pilot plant. Although it is important to note that the pilot plant will neither likely use the same materials, nor involve water cooling, and thus is expected to operate at higher temperatures for which no established code basis exists for materials

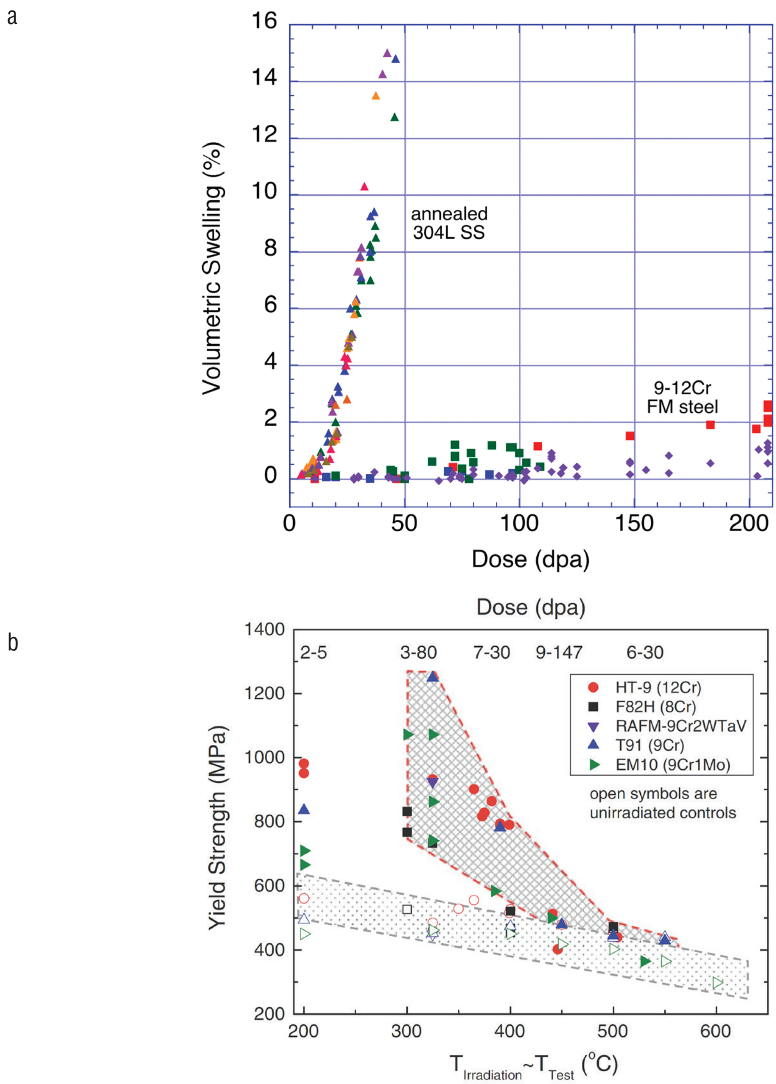

FIGURE 4.3 (a) Comparison of neutron radiation induced swelling of an austenitic stainless steel (annealed type 304L) and a 9-12 percent ferritic/martensitic steel in the temperature range from 400 to 550°C. (b) Yield strength of ferritic martensitic steels, including the reduced activation ferritic martensitic alloys F82H and 9Cr2WTaV as a function of temperature and neutron dose. Note the irradiation temperature and tensile testing temperature were approximately the same. SOURCE: (a) Republished with permission of Annual Reviews, Inc., from S.J. Zinkle and L.L. Snead, 2014, Designing radiation resistance in materials for fusion energy, *Annual Review of Materials Research* 44:241-267; permission conveyed through Copyright Clearance Center, Inc. (b) Reprinted from R.J. Kurtz and G.R. Odette, 2019, "Overview of Reactor Systems and Operating Environments for Structural Materials in Fusion Reactors," pp. 51-102 in *Structural Alloys for Nuclear Energy Systems,* Elsevier, Amsterdam, The Netherlands; copyright 2019, with permission from Elsevier, http://www.elsevier.com.

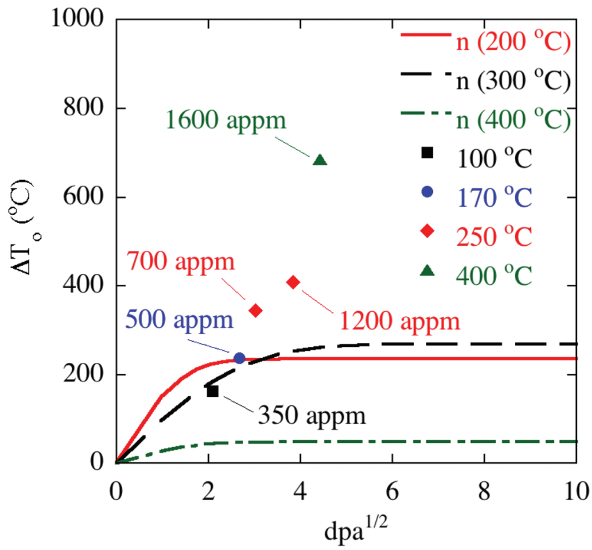

FIGURE 4.4 Predicted (lines) and measured (points) shift in the Master curve transition temperature ΔT_o, of reduced activation ferritic martensitic alloys, which is a measure of the increase in the ductile to brittle transition temperature. SOURCE: Reprinted from Y. Dai, G.R. Odette and T. Yamamoto, 2012, "The Effects of Helium in Irradiated Structural Alloys," pp. 141-193 in *Comprehensive Nuclear Materials* (R.J.M. Konings, ed.), Elsevier, Amsterdam, The Netherlands; copyright 2012, with permission from Elsevier, http://www.elsevier.com.

licensing. The structural design criteria developed for ITER, and already being used for other fusion concept designs, can provide a starting point for the design of a pilot plant. Thus, robust mechanical property, corrosion, fabrication, and irradiation effects databases will need to be established that meet the requirements of appropriate regulatory authorities, including those consisting of high-temperature and time-varying stress state. This necessitates significant materials R&D to enable the design and function of all in-vessel and ex-vessel structural and functional materials in the fusion pilot plant environment.

Finding: Confidence exists in the ability of low-activation ferritic martensitic alloys to survive D-T neutron-induced degradation up to a dose of 50 dpa/500 appm He (~5 MW-year m^{-2}) at temperatures between 400 and 550°C; however, partially integrated testing is required to provide confidence in the performance of reduced activation ferritic martensitic components to the cyclic loading and environmental degradation required for Phase 1 and 2 operation of the pilot plant.

Finding: Due to the anticipated higher operating temperature of a fusion pilot plant, the design criteria and licensing will be significantly different than for light water fission reactors or ITER, and will require development to address unique components, higher operating temperature and time-varying stress state, corrosive coolants, and stress/temperature gradients.

Recommendation: The materials engineering community, supported by the fusion community and the Department of Energy, should develop high-temperature structural design criteria that incorporate creep, fatigue, and corrosion behavior of in-vessel and ex-vessel structural and functional components to enable the engineering design and licensing of a fusion pilot plant as part of the conceptual design activities.

Advanced manufacturing and complex material component design have transformative potential,[27] yet research is required to move beyond the early stage of developing these alloys and composites. This includes investigating neutron radiation effects, chemical compatibility and corrosion, response to plasma material interactions and tritium permeation, and component performance and degradation in the complex neutron, plasma material, and thermal-mechanical loading conditions. Studies will need to proceed from relatively simple single variable experiments to very complex, fully integrated, multiple-variable tests prior to Phase 1 pilot plant operation.

For aneutronic fusion fuel cycles, the neutron flux and corresponding neutron-induced degradation and neutron activation concerns are reduced by one to two orders of magnitude. However, new concerns are introduced by the much larger heat and ion particle implantation into the near surface region of the first wall armor components. As well, the majority of the ion flux will consist of insoluble helium, which can degrade near surface thermal and mechanical properties. The implantation of helium into materials can cause blistering and spallation that can produce material loss. The maturity of materials for applications in high heat flux and ion implantation applications in advanced fuel cycles is at a low TRL that necessitates further R&D, which should be defined as part of a more detailed technology roadmap for such fusion concepts.

Recommendation: The Department of Energy should support a research program, including facilities to provide a limited volume prototypic neutron source for testing of advanced structural and functional materials and to assess neutron degradation limits of RAFM alloys beyond 5 MW-year m^{-2}.

Recommendation: The Department of Energy should support facilities for integrated blanket testing in representative time-varying heat flux, mechanical

loading, and corrosive environments, to identify, evaluate, and finalize a high-confidence, robust design for structural and functional materials.

Innovations and Research Needed for Plasma Heating Systems and Actuators

A broad range of heating and current drive technologies have been developed and employed in existing fusion experiments. These include gyrotrons and waveguides for electron cyclotron heating and current drive, antennas for ion cyclotron and lower hybrid wave heating and current drive, and neutral beams, including high-energy negative ion beams. Examples of areas requiring further R&D include high-frequency gyrotrons to enable electron cyclotron heating and current drive at high magnetic field, antenna structures compatible with high neutron and heat flux, and beam injection systems compatible with tritium breeding blankets.

Solutions for the plasma heating systems and actuators for a fusion pilot plant are not in hand. In particular the normalized costs (dollars per watt) could be a significant factor in the overnight cost of the fusion pilot plant, while the electrical efficiency of the drivers/actuators clearly play a role in meeting its net electrical power goal. In addition, the durability of these heating/actuator engineering components exposed to the harsh fusion environment will be important to the operation times and costs of the fusion pilot plant.

Finding: While ongoing advances in heating and current drive actuators have increased confidence in their capabilities to effectively drive and control fusion systems, significant progress is needed to demonstrate cost-effectiveness and compatibility with the needs of a pilot plant.

Finding: A sustained pilot plant will require very high efficiency, months-long duration operation for actuators used in the stationary phase. Innovations in physics, such as very high bootstrap fraction for tokamaks, and in technology, such as radio frequency and beam technology that is both cost-effective and compatible with the neutron and heat flux environment, are needed. Actuators must be robust, reliable, and efficient for various phases of the operation in the pilot plant's fusion environment.

Finding: A pulsed pilot plant will require very high efficiency, cost-effective, durable, and in some cases high repetition rate drivers. Large reductions in cost per joule over existing drivers are required.

Recommendation: The Department of Energy should invest in the development of actuator technology and supporting theory that is compatible with the requirements of leading pilot plant concepts.

Innovations Needed for Closing the Fuel Cycle

A D-T fusion reactor cannot function without a closed tritium fuel cycle, and this represents a fundamental feasibility issue for D-T fusion power production. Tritium is a difficult species for control, accounting, and safety, yet it is critical to the fusion fuel cycle. In order for fusion to realize its maximum potential for safe operation and benign environmental impacts, high-fidelity understanding of all processes involving tritium is required. The tritium fuel cycle has a very broad footprint on any fusion facility, which involves tritium burn fraction in the plasma, tritium processing time from plasma exhaust to fueling, breeding of tritium in the blanket surrounding the plasma, extraction efficiencies from the breeder and coolant streams, tritium losses from and inventories in the fusion core, near-core and ex-core subsystems, and many more that constitute a complex and interacting system. This is an essential capability for a D-T fusion pilot plant, and advances in these areas are required to meet the ambitious goals of a fusion pilot plant in the 2035-2040 timeframe.

There are presently many blanket concepts being considered to meet the simultaneous demands of fusion power removal, neutron shielding, and tritium breeding. A number of different blanket concepts have been proposed and include a variety of solid and liquid blankets configurations to achieve these goals; however, all concepts are at low technology readiness. This low readiness has to be addressed, since the blanket has significant design implications regarding the tritium breeding ratio, power conversion, and maintenance scheme for the pilot plant. The choice of coolant and the range of operating temperature of the blanket is important for overall efficiency of the pilot plant, and this has far-reaching consequences on the design performance of the blanket. The blanket also serves as a primary component in shielding sensitive components, such as magnets, from the deleterious effects of neutrons and high-energy photons, and as such, the radial thickness of the blanket is a key consideration in setting the overall size of the fusion pilot plant.

Finding: Advancing the technology readiness of blanket technology is required in order to select and optimize the blanket concept for a fusion pilot plant.

Virtually all of the technologies related to the tritium fuel cycle are at low technical readiness, with wide uncertainty in parameters that describe tritium migration through materials and across interfaces, tritium retention in bulk solids and liquids, and tritium retention and behavior in plasma-facing materials. Extraction of tritium from either liquid or solid breeder materials is still highly uncertain, and the development of tritium barriers has been largely unsuccessful. ITER will provide a strong step in tritium processing and the fueling/exhaust tritium loop, with higher amounts of tritium required in the future (relative to ITER). Breeder material behavior and interactions are still at a low level of understanding.

The breeding and recovery of tritium as it is processed raises a number of safety concerns to protect workers, the public, and the environment. Tritium is highly mobile and can readily permeate through metallic components, especially at elevated temperatures. ITER has a 4 kg maximum tritium inventory (~1.5×10^{18} Bq). As noted in Chapter 3, it is desirable to minimize the tritium inventory to ~1 kg. Also due to the sustained operation of a pilot plant, continuous processing technologies will be required. Expected tritium release limits are extremely low, and tritium needs to be accurately tracked to assure safety and proliferation. The grand challenges of tritium require improved scientific understanding of many interconnected phenomena including permeation, radiolytic chemistry, surface science and kinetics, liquid metal magnetohydrodynamics, and mass transfer. Systems and processes must be developed that can efficiently and safely continuously process tritium at flow rates and quantities far beyond current practice. Some of the technical issues associated with tritium control and recovery may be addressed by advanced fission reactors using lithium-based molten salts, and progress in these fission energy efforts may be applicable also to fusion systems.

Finding: Maintaining low tritium inventory in a fusion plant is important for public safety, licensing, and many other considerations. Technologies that can enable decreasing tritium inventory in the fusion machine and the tritium processing plant are needed.

Direct internal recycling of tritium is one example of a technology with the potential to reduce tritium processing rates, and innovations that can enable direct internal recycling or similar technologies will be important. One challenge with direct internal recycling is that many of the impurities damage or poison known chemical processing methods and technologies for separation. Catalysis and removal of these corrosive species from the hot plasma is very challenging, but there are some potential avenues to be explored. Another important part of controlling overall tritium inventory is minimizing the captive inventory within the blanket material. The tritium must be rapidly recovered and kept out of collateral materials in order to minimize tritium inventory within the breeding loop. Direct internal recycling technologies, blanket tritium inventory reduction, or other similar methods to reduce the tritium inventory will need development before a fusion pilot plant.

Finding: Improvements in tritium accountability methods that can be applied in continuously operating fusion plants are needed and should be demonstrated in a fusion pilot plant.

Recommendation: The Department of Energy should support research projects with the simultaneous objectives of reducing tritium inventory

while increasing tritium processing rates that incorporate concepts such as process intensification. Technologies should be demonstrated prior to the construction of the tritium plant of a fusion pilot plant.

Demonstration of tritium breeding and extraction technologies in the fusion blanket will be critical to the function of a fusion pilot plant and have not been demonstrated to date, although new advanced fission reactors using lithium-bearing fluoride salts may address some key questions relevant to a fusion pilot plant. The specific tritium breeding and extraction concept that will be implemented in a fusion pilot plant should be demonstrated during the design phase to provide reasonable confidence that it will work within a fusion pilot plant. A demonstration should include the ability to mitigate materials degradation of system materials due to exposure to blanket materials such as Pb-Li, FLiBe, or other relevant breeding blanket materials. If tritium extraction methods utilize halides, a method will need to be developed to ensure no halides or other potentially reactive impurities migrate to the tritium systems (e.g., a fluorine or impurity removal trap).

Recommendation: The Department of Energy should support research projects and a demonstration to increase technology readiness and provide confidence that tritium breeding and extraction technologies can achieve fuel sustainability. Technologies should be demonstrated prior to the construction of the tritium plant of a D-T fusion pilot plant.

Finding: Tritium emissions from a fusion energy pilot plant need to be controlled to meet applicable NRC guidelines. A fusion pilot plant should demonstrate implementation of tritium emission control measures and the ability to maintain emissions within NRC guidelines for a FOAK fusion power plant or a pathway to achieve the required emissions reduction.

PARTICIPANTS IN DEVELOPING A PILOT PLANT

The design, construction, and operation of a fusion pilot plant will require addressing scientific, engineering, and regulatory issues in an integrated fashion utilizing a broad spectrum of skills. While the United States is a leader in fusion research, the United States has not built a fusion facility of the scale of a pilot plant. Thus, new additional skills beyond that which currently exist will be needed, while continuing to leverage strengths of the program. The pilot plant teams would be composed of fusion developers, component manufacturers, EPC companies, universities, national laboratories, and potentially investor-owned utilities.

Large projects such as a pilot plant require strong teams of engineers, including systems engineering, project managers, and individuals with licensing experience. Some of these skills currently exist within the program but will have to be augmented. Creating new teams is an opportunity to add members with the requisite skills.

Embracing diversity, equity, and inclusion is key to building successful teams to solve the challenges that fusion faces. This is multi-faceted, and at the highest level, means a team of people that approach these challenges from a multitude of viewpoints. Different viewpoints arise from many different sources, including, but not limited to technical expertise, a person's life experiences, gender, ethnic background, age, and many others. It is important to note that diverse teams are more effective at solving problems than those that are not diverse; however, those teams must work together, otherwise they are less effective than non-diverse teams.[28] The recently released fusion community plan[29] recognizes the importance of diverse teams, identifying the cross-cutting opportunity to "Embrace diversity, equity, and inclusion, and develop the multidisciplinary workforce required to solve the challenges in fusion and plasma science."

The need to embrace diversity, equity, and inclusion is not new, nor newly discovered. There are many studies, including very recent ones, that support this conclusion and provide evidence that while there has been progress, we have a long way to go. Studies such as the National Academies' *Promising Practices for Addressing the Underrepresentation of Women in Science, Engineering, and Medicine: Opening Doors,*[30] *Expanding Underrepresented Minority Participation,*[31] and *Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine*[32] provide actionable recommendations to drive positive systemic change. Change cannot happen without a visible and obvious emphasis.

Finding: The need to embrace diversity, equity, and inclusion is not new, nor newly discovered. Change cannot happen without a visible and obvious emphasis.

Recommendation: The participants in the development of the pilot plant should execute the recommendation of the Community Planning Process to "Embrace diversity, equity, and inclusion, and develop the multidisciplinary workforce required to solve the challenges in fusion and plasma science."

A continued tight coupling between the ongoing research teams in the fusion program and the pilot plant teams will be needed. Universities have had a significant role in fusion research, have built and operated experiments, and have been key in workforce development. This role needs to continue, with increased effort on technology development, which had been previously reduced and will now have to be strengthened. Some of the universities have also played a major role in spinning-off privately funded fusion developers.

Discussions with component manufacturers surfaced a need for funding stability as an important requirement for their partnership in this effort. Companies are interested in working on fusion and developing technology and tooling needed to construct components; however, past experience reveals that industry requires a stable revenue stream to attract, develop, and retain the expertise that is needed. Without such stability, the expertise that is developed in industry will go away. This has occurred previously in the fusion program and is another motivation for an accelerated program to ensure that the appropriate skills are developed and retained in industry.

National laboratories have played a large role in the fusion program ranging from scientific research and technology development, to operation of large magnetic fusion facilities. They operate tritium facilities, including previously a D-T fusion facility, and have capabilities for siting nuclear facilities. They also perform a broad range of research from basic to applied. Similarly, the National Nuclear Security Administration has operated facilities at national laboratories and at the University of Rochester to advance the scientific understanding of inertial confinement fusion. Experience gained at these facilities in addressing issues related to tritium handling and neutron production can benefit the fusion pilot plant effort and add diversity in perspective.

DOE Fusion Energy Sciences has operated national facilities at national laboratories, industry, and universities. Princeton Plasma Physics Laboratory hosted TFTR (D-T tokamak) and now the NSTX-U facility. A private company, General Atomics, has built and operates the DIII-D National Fusion Facility on behalf of the Department of Energy. Similarly, a university, Massachusetts Institute of Technology, previously built and operated Alcator C-Mod. These DOE-funded facilities have contributed to numerous scientific advances and have achieved high values of the Lawson parameter, approaching conditions required for fusion breakeven.

In the United States, there is far more private investment in fusion technologies today compared to 10 years ago. This private investment is a positive development because it enables parallel developmental paths, which is key to realizing success in this challenging technology. Private investors expect a return on their investments. Milestones need to be achieved that demonstrate progress toward goals using a timeline that maps to market needs.

Most of the privately-funded fusion technology companies have tapped into the expertise at the national laboratories and universities by directly funding work, by hiring staff from the national laboratories, or through new funding programs such as Innovation Network for Fusion Energy (INFUSE) and the Advanced Research Projects Agency-Energy (ARPA-E) BETHE (Breakthroughs Enabling Thermonuclear-fusion Energy), including diagnostic teams and GAMOW

(Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts), which is jointly funded by FES and ARPA-E. It was noted that currently INFUSE only supports national laboratories.

Finding: Teams composed of private industries, national laboratories, and universities bring together important strengths: industry brings the focus on deploying a usable product on a timeframe that will meet market needs, and national laboratories and universities bring innovation and deep technical expertise.

Recommendation: The Department of Energy should further encourage access of private industry to the broad range of technical experts resident at the national laboratories and universities.

Recommendation: The Department of Energy (DOE) should use and expand the new programs to partner with industry in support of the pilot plant design, and DOE should include all Fusion Energy Sciences-funded researchers, including those at universities and private companies, in the INFUSE program.

MODELS FOR PUBLIC-PRIVATE PARTNERSHIPS

Over the last several decades, fusion energy research has involved government-sponsored programs, and for larger research efforts, international collaboration with the ITER being the largest and most sustained example. However, over the last two decades multiple private-sector efforts have been initiated to develop fusion energy concepts. The committee heard from the industry consortium that represents many of these companies, the Fusion Industry Association, along with representatives from several companies developing fusion technology and concepts. As of today, more than $1 billion of private-sector investment has already been made in fusion systems.[33]

As noted in the "Economic Considerations" section in Chapter 3, a number of different federal government cost-sharing approaches have been utilized to stimulate new energy production technology, including direct cost share, tax incentives, loan guarantees, grants to specific companies, ARPA-E funding of public-private projects, prizes, and payment for milestones. Although there are significant differences in terms of technology maturity, the NASA Commercial Orbital Transportation Services (COTS) program has realized substantial cost reduction through an innovative cost- and risk-sharing approach that involved a fixed-price payment-for-milestones contracting structure to private-sector companies working to develop crew and cargo space transportation capabilities. In parallel, NASA pursued its conventional Artemis program to develop deep space exploration capabilities, which could also satisfy similar capabilities to low Earth orbit if necessary. One of the first COTS awards was in 2006 to the start-up company SpaceX, which had been founded in 2002. By 2008 SpaceX had conducted its first successful launch of the single-engine Falcon 1, by 2012 it made its first cargo delivery to the International Space Station using the Falcon 9, by 2018 it had captured over half of the worldwide market for commercial space launch services, and by 2020 it became the first commercial company to launch humans to space. Successful technology development efforts funded by private investment involve strong and positive public incentives to systematically address areas of technology and market risks with the ultimate objective of purchasing a commercially viable, cost-effective product or service. Public-private partnerships using payment-for-milestones contracting, versus traditional cost plus fee contracting, reinforce built-in incentives to be efficient, timely, and entirely success oriented. This is a principal reason that the NASA COTS model has emerged as a recommended possible strategy for advanced fission energy[34] as well as for fusion,[35] although other models have also been used for developing advanced fission energy including loan guarantees and direct cost share agreements as being pursued in the Advanced Reactor Development Program.[36] Furthermore, the recently enacted bill HR-133 Sec. 2008 has defined a milestone-based fusion energy development program.

Public cost-share support of private-sector efforts to develop fusion energy are well justified by the long-term societal benefits of successful commercial deployment of dispatchable, sustainable clean energy technology. However, it is important to note that SpaceX would likely not have been successful in such a short timeframe without access to NASA's technical expertise and key infrastructure including launch range facilities. In the same way, it remains essential that DOE sustain a strong base program in fusion energy science and technology, including supporting infrastructure and research at national laboratories and universities, and pursuing development of a fusion pilot plant as recommended in this report. As discussed above, the DOE INFUSE program and the BETHE and GAMOW programs are designed to enable private-sector companies to access these capabilities.

Since the fusion program has not used a milestone-based public-private partnership previously, gaining experience with such a program would be valuable. The following two examples of research that are needed are meant to illustrate how such a program could be applied.

The response of materials to neutrons in the fusion environment is of universal interest because they are present in all fusion concepts, even though the relative fraction of fusion energy carried by neutrons and their energy varies. A particular challenge is faced in D-T fusion because the 14 MeV neutrons are at a much higher energy than from fission, and therefore the relevance of materials exposed in existing reactors is limited. Furthermore, it is important that the exposure environment (thermal, chemical) is sufficiently representative of the fusion concept. Therefore, one must consider the development of dedicated capabilities and facilities that can determine the response of materials in a fusion neutron environment. This can lend itself to a public-private partnership because there are both scientific frontiers to explore and practical questions to answer for private fusion developers. If the facility can serve a broad set of developers or concepts, the combined financial and technical resources from the government and private could be leveraged. Furthermore, the cost-effective design, construction, and operation of such a facility would be a target for a milestone payment program since the scientific requirements of the neutron exposure are already well understood. This program could include cost shares on the near-term maturation of neutron source technology presently being developed in the private sector.

A related and synergistic topic is the response of superconductor magnets to the fusion environment. Many fusion concepts rely on strong magnetic fields produced by electromagnets. These are almost always superconductor magnets because they consume minimal electricity to operate. However, the fusion neutrons can affect the superconductors and therefore impact the overall performance and lifetime of the superconductor coils. Simultaneously, there are substantial and multiple efforts on the development of HTS magnets in the private sector. A milestone-based public-private partnership that focuses on the magnet performance evolution under neutron bombardment in a shared facility would be a high leverage opportunity.

Finding: The NASA COTS program achieved remarkable success in developing new commercially competitive space transportation capabilities at significantly less cost to the government and with an accelerated schedule using a payment-for-milestones public-private partnership.

Finding: While the NASA COTS model holds promise, in general the TRL for space transportation systems is substantially higher than the TRL for major fusion energy systems. Due to the strategic importance of crew and cargo space transportation capabilities to the International Space Station and beyond low Earth orbit, NASA pursued a conventional technology development program (now called Artemis) in parallel with its COTS program to mitigate the commercial investment risk and to serve longer term deep space exploration goals.

Recommendation: The Department of Energy should evaluate and identify the best model for public-private partnerships to accelerate development and reduce government cost for a fusion pilot plant. Note that the different phases of the development, including conceptual design and technology roadmap, detailed engineering design, construction and operation, may involve different or incremental public private partnership models, including fixed-price payment for milestones.

ITER CONTRIBUTIONS TO A PILOT PLANT

As an ITER member, the United States receives access to all ITER intellectual property (IP); the Department of Energy is responsible for determining how that IP will be available. ITER-related technologies are accessible to the U.S. fusion industry through partnerships with DOE national laboratories and universities. U.S. fusion and related industries benefit from the technologies, know-how, and experience that results from U.S. engagement in ITER. Leveraging the experience gained from the ITER project will be important to meeting the aggressive timescale for a pilot plant.

The United States is responsible for hardware design and manufacturing for 12 different ITER systems. Experience in developing specifications for ITER hardware procurements and overseeing the design, fabrication, and delivery of the hardware that meets regulatory requirements is an important foundational step that will benefit the design and deployment of a fusion pilot plant. While a pilot plant will differ considerably from ITER, and may not even be a tokamak configuration, much of the experience gained through the ITER process is relevant to a pilot plant regardless of its configuration. The ITER systems that the United States is responsible for that could fit into this category include instrumentation and control, magnet conductors, steady-state electrical networks, plasma diagnostics, isotope separation, and vacuum systems. If the U.S. fusion pilot plant is a tokamak, then there are several specialized systems from the U.S. ITER effort that could be relevant, including the disruption mitigation system, which limits damage to internal components from off-normal events, high-efficiency radio frequency power transmission lines for heating systems, and the central solenoid, which produces most of the plasma current needed in a tokamak. In addition, the United States is contributing to the design of the tokamak blanket/shield and the in-vessel coils for plasma control.

Examples of how ITER activities benefit the U.S. fusion industry broadly include:

- *Tools and strategies for plasma control and performance.* ITER, in conjunction with the international community, has led to advances in modeling, prediction, avoidance, and control of plasma transients and disruptions in tokamaks; supporting technologies and techniques have also been developed. Non-tokamak fusion devices can also benefit from the improved understanding of plasma behavior derived from ITER R&D.
- *Superconducting magnet technologies.* The accumulated mechanical properties of structural materials at cryogenic operating temperatures is an important asset for all magnet designs. In addition, lessons learned on the complexity and scale of ITER magnet systems can inform solutions

for feedthroughs and joints and production/testing strategies, even if new superconductors are likely to be used in the pilot plant.

- *Radiation transport analysis.* Higher resolution and faster radiation computational analysis tools have been applied to understanding ITER shielding and safety requirements, including shutdown dose rates. These tools, combined with advanced modeling and simulation, will be highly relevant to the design qualification and safe operation of future fusion devices and power plants
- *High-powered plasma heating.* State-of-the-art heating and current drive technologies developed in the United States and by ITER partners for a nuclear facility could be broadly applied across many magnetic confinement configurations.
- *D-T fuel cycle technologies.* The knowledge and application of the ITER tritium plant design directly supports the development of a fusion pilot plant in that the processing rate of hydrogen isotopes is much greater than current facilities use and scale-up as well as validation of many components will be completed as part of constructing the ITER fuel cycle. The ITER design includes ash and impurity removal; recapture of the hydrogen; separation of the hydrogen isotopes; and recycling of the isotopes back into the fuel stream. Specific technologies to be developed by ITER include palladium-silver permeators; tritium impurity catalysis and removal; cryopumping of tritium; tritium storage and delivery; and advanced tritium process modeling. In addition to the fuel process loop, the ITER design includes a detritiation system that minimizes tritium releases to the environment. Progress has been made on many fronts in development of these systems for ITER, but challenges remain in component scale-up and system integration.
- *Continuous plasma fueling.* ITER has led the development of continuous pellet fueling systems for long pulse operations. Pellet fueling may be an effective strategy for efficiently and reliably delivering hydrogen fuels to plasmas in various device configurations.
- *Fusion materials.* ITER-scale requirements drove a demonstration path for the development and selection of appropriate plasma-facing and divertor materials that can handle the neutrons, magnetic fields, and heat flux of the ITER fusion environment. Even though the environment of a pilot is expected to be harsher (high power density, neutron fluence, different coolants, and higher operating temperature) this is foundational work for next-generation fusion materials and components.
- *Fusion power and particle handling.* ITER power levels and pulse length will exceed that of any current fusion device. The power and particle handling demands of many fusion pilot plant designs will require full steady state

operation solutions informed by ITER R&D. This includes actively cooled internal components and high-speed tritium-compatible vacuum pumps.

- *Burning plasma science.* ITER's mission is to achieve plasma energy gain of 10 and access the burning plasma regime. This has two impacts on a fusion pilot plant. The first impact is through the development of the detailed science tools needed to predict ITER's performance. These tools can be applied to a fusion pilot plant, with the impact being dependent on the pilot's configuration. These tools can be effective immediately. The second impact would be anticipated by the experimental achievement of the burning plasma regime after 2035 when D-T operations are expected to start in ITER. The insights gained from these results could be important to the fusion pilot plant starting operations at a similar time.

ITER represents a major step forward in fusion science and technology funded by the U.S. government through the ITER agreement. The knowledge gained by participating in the ITER project is one of the key motivations for the United States to continue its support.

Recommendation: The Department of Energy should assure maximum possible access to ITER information for the members of the fusion pilot plant design teams.

INTERNATIONAL COLLABORATIONS

The United States has had major international collaborations in fusion research in addition to ITER since the fusion program was declassified in 1958. U.S. scientists participate in experiments on major facilities throughout the world and in particular on the largest cutting-edge facilities including Asdex Upgrade and W7-X in Germany, EAST in China, JET and MAST-U in the United Kingdom, K-STAR in Korea, LHD and JT60-SA in Japan, WEST in France, and many other smaller facilities around the world. International scientists participate extensively in U.S. experiments. Collaborations span a broad range of topics including not only experiments but also theory, modeling, and technology development. The United States provides neutron irradiation facilities for collaboration with Japanese and European fusion programs. Construction of a pilot plant in the United States would provide an opportunity to expand these collaborations. In some technology areas, international collaborators would be able to provide experience and access to test facilities, which are not available in the United States. This can be mutually beneficial.

NOTES

1. S. Baalrud, N. Ferraro, L. Garrison, N. Howard, C. Kuranz, J. Sarff, and W. Solomon, 2020, "A Community Plan for Fusion Energy and Discovery Science," https://arxiv.org/abs/2011.04806.
2. Fusion Energy Sciences Advisory Committee, 2018, "Fusion Energy Sciences Advisory Committee Report: Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy," updated February 15, https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf?la=en&hash=A748443D03AD591E340AD046D53F86537B37FAB0.
3. S. J. Zinkle and J. T. Busby, 2009, Structural materials for fission & fusion energy, *Materials Today,* 12:12-19, https://doi.org/10.1016/S1369-7021(09)70294-9.
4. S. J. Zinkle and G. S. Was, 2013, Materials challenges in nuclear energy, *Acta Materialia* 61:735-758, https://doi.org/10.1016/j.actamat.2012.11.004.
5. S. J. Zinkle and L. L. Snead, 2014, Designing radiation resistance in materials for fusion energy, *Annual Review of Materials Research* 44:241-267, https://doi.org/10.1146/annurev-matsci-070813-113627.
6. R. J. Kurtz and G. R. Odette, 2019, "Chapter 3 - Overview of Reactor Systems and Operating Environments for Structural Materials in Fusion Reactors," Pp. 51-102 in *Structural Alloys for Nuclear Energy Systems,* Elsevier, Amsterdam, doi:10.1016/B978-0-12-397046-6.00003-4.
7. S. J. Zinkle and L. L. Snead, 2014, Designing radiation resistance in materials for fusion energy, *Annual Review of Materials Research* 44:241-267, https://doi.org/10.1146/annurev-matsci-070813-113627.
8. A.C. Klein, 2017, *ANS Nuclear Grand Challenges*, special report, American Nuclear Society, June.
9. National Academies of Sciences, Engineering, and Medicine, 2019, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*, Washington, DC. The National Academies Press, https://doi.org/10.17226/25331.
10. National Academies of Sciences, Engineering, and Medicine, 2019, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*, Washington, DC. The National Academies Press, https://doi.org/10.17226/25331.
11. R. J. Goldston, 2012, Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks, *Nuclear Fusion* 52:013009, https://doi.org/10.1088/0029-5515/52/1/013009.
12. T. Eich, B. Sieglin, A. Scarabosio, W. Fundamenski, R. J. Goldston, and A. Herrmann, 2011, Inter-ELM power decay length for JET and ASDEX upgrade: measurement and comparison with heuristic drift-based model, *Physical Review Letters* 107:215001, https://doi.org/10.1103/PhysRevLett.107.215001.
13. P. B. Snyder, R. J. Groebner, J. W. Hughes, T. H. Osborne, M. Beurskens, A. W. Leonard, H. R. Wilson, and X. Q. Xu, 2011, A first-principles predictive model of the pedestal height and width: development, testing and ITER optimization with the EPED model, *Nuclear Fusion* 51:103016, https://doi.org/10.1088/0029-5515/51/10/103016.
14. T. E. Evans, R. A. Moyer, J. G. Watkins, T. H. Osborne, P. R. Thomas, M. Becoulet, J. A. Boedo, et al., 2005, Suppression of large edge localized modes with edge resonant magnetic fields in high confinement DIII-D plasmas, *Nuclear Fusion* 45:595, https://doi.org/10.1088/0029-5515/45/7/007.
15. D. D. Ryutov, 2007, Geometrical properties of a "snowflake" divertor, *Physics of Plasmas* 14:064502, https://doi.org/10.1063/1.2738399.
16. M. Kotschenreuther, P. Valanju, S. M. Mahajan, L. Zheng, L. Pearlstein, R. Bulber, J. Canik, and R. Maingi, 2010, The super X divertor (SXD) and a compact fusion neutron source (CFNS), *Nuclear Fusion* 50:035003, https://doi.org/10.1088/0029-5515/50/3/035003.
17. H. Y. Guo, C. F. Sang, P. C. Stangeby, L. L. Lao, T. S. Taylor, and D. M. Thomas, 2017, Small angle slot divertor concept for long pulse advanced tokamak, *Nuclear Fusion* 57:044001, https://doi.org/10.1088/1741-4326/aa5b46.

18. J. E. Menard, T. Brown, L. El-Guebaly, M. Boyer, J. Canik, B. Colling, R. Raman, et al., 2016, Fusion nuclear science facilities and pilot plants based on the spherical tokamak, *Nuclear Fusion* 56:106023, https://doi.org/10.1088/0029-5515/56/10/106023.
19. H. Y. Guo, H. Q. Wang, J. G. Watkins, L. Casili, B. Covele, A. L. Moser, T. Osborne, C. M. Samuell, et al., 2019, First experimental tests of a new small angle slot divertor on DIII-D, *Nuclear Fusion* 59:086054, https://doi.org/10.1088/1741-4326/ab26ee.
20. Fusion Energy Sciences Advisory Committee, 2018, "Fusion Energy Sciences Advisory Committee Report: Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy," updated February 15, https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf?la=en&hash=A748443D03AD591E340AD046D53F86537B37FAB0.
21. D. Larbalestier, A. Gurevich, D. M. Feldmann, and A. Polyanskii, 2001, High-T_c superconducting materials for electric power applications, *Nature* 414:368-377, https://doi.org/10.1038/35104654.
22. W. H. Feitz, C. Barth, S. Drotziger, W. Goldacker, R. Heller, S. I. Schlachter, and K. P. Weiss, 2013, Prospects of high temperature superconductors for fusion magnets and power applications, *Fusion Engineering and Design* 88:440, https://doi.org/10.1016/j.fusengdes.2013.03.059.
23. S. J. Zinkle, and L. L. Snead, 2014, Designing radiation resistance in materials for fusion energy, *Annual Review of Materials Research* 44:241-267, https://doi.org/10.1146/annurev-matsci-070813-113627.
24. Y. Dai, G. R. Odette, and T. Yamamoto, 2012, "The Effects of Helium in Irradiated Structural Alloys," Pp. 141-193 in *Comprehensive Nuclear Materials* (R. J. M. Konings, ed.), Elsevier: Amsterdam, https://doi.org/10.1016/B978-0-08-056033-5.00006-9.
25. R. J. Kurtz and G. R. Odette, 2019, "Chapter 3 - Overview of Reactor Systems and Operating Environments for Structural Materials in Fusion Reactors," Pp. 51-102 in *Structural Alloys for Nuclear Energy Systems*, Elsevier, Amsterdam, doi:10.1016/B978-0-12-397046-6.00003-4.
26. Y. Dai, G. R. Odette, and T. Yamamoto, 2012, "The Effects of Helium in Irradiated Structural Alloys," Pp. 141-193 in *Comprehensive Nuclear Materials* (R. J. M. Konings, ed.), Elsevier: Amsterdam, https://doi.org/10.1016/B978-0-08-056033-5.00006-9.
27. Fusion Energy Sciences Advisory Committee, 2018, "Fusion Energy Sciences Advisory Committee Report: Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy," updated February 15, https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf?la=en&hash=A748443D03AD591E340AD046D53F86537B37FAB0.
28. S. L. Robbins, 2018, *What If? Short Stories to Spark Inclusion and Diversity Dialogue,* 10th Anniversary Edition, Boston: MA: Nicholas Brealey Publishing.
29. S. Baalrud, N. Ferraro, L. Garrison, N. Howard, C. Kuranz, J. Sarff, and W. Solomon, 2020, "A Community Plan for Fusion Energy and Discovery Science," https://arxiv.org/abs/2011.04806.
30. National Academies of Sciences, Engineering, and Medicine, 2020, *Promising Practices for Addressing the Underrepresentation of Women in Science, Engineering, and Medicine: Opening Doors*, Washington, DC, The National Academies Press, https://doi.org/10.17226/25585.
31. National Research Council, 2011, *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads*, Washington, DC, The National Academies Press, https://doi.org/10.17226/12984.
32. National Academies of Sciences, Engineering, and Medicine, 2018, *Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine,* Washington, DC: The National Academies Press, https://doi.org/10.17226/24994.
33. D. Kramer, 2020, "Investments in Privately Funded Fusion Ventures Grow," updated October 13, *Physics Today* doi:10.1063/PT.6.2.20201013a.
34. Nuclear Innovation Alliance, 2019, "In Search of a SpaceX for Nuclear Energy," https://www.nuclearinnovationalliance.org/search-spacex-nuclear-energy.

35. Federal Register, 2020, "Cost-Sharing Partnerships with the Private Sector in Fusion Energy," https://www.federalregister.gov/documents/2020/04/20/2020-08312/cost-sharing-partnerships-with-the-private-sector-in-fusion-energy.
36. Office of Nuclear Energy, 2020, "Advanced Reactor Demonstration Program," https://www.energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-demonstration-program.

5

Strategy and Roadmap for a Pilot Plant

In response to the statement of task, the committee took the feedback from the utilities into account, which framed the timeline requirements for the pilot plant. As noted above, the electrical utilities in the United States are working toward the transition to low-carbon emission electricity production by 2050. This motivates exploring a schedule to bring a pilot plant into operation between 2035 and 2040: this is aggressive relative to recent construction of large fusion facilities and other countries' fusion program plans, with the exception of China's CFETR program and the United Kingdom's recently announced STEP program. Both programs seek to be the first to put electricity from fusion on the grid. Unlike the program plans developed by the Community Planning Process (CPP),[1] which considered a comprehensive bottom-up approach that is appropriate to developing a program and includes many elements beyond those associated with a pilot plant, the committee took a more targeted approach to explore what would be needed to bring a pilot plant into operation as soon as possible for fusion to be considered as a viable generation alternative during the investment window. This schedule-driven approach will require the execution of many parallel activities and engagement of a broad group of participants in the private and public sectors as discussed in Chapter 4. In parallel with the development of this report, Fusion Energy Sciences Advisory Committee (FESAC) is addressing the schedule implications and priorities of the CPP report. Ultimately, it will be necessary to reconcile the upcoming FESAC report and its priorities with the top-down schedule-driven approach described herein.

In the 2019 report *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research* (hereafter the "*Burning Plasma* report"),[2] the tokamak concept was identified as the primary track to a fusion pilot plant and the stellarator as the leading alternative. The statement of task for this report does not presume which fusion concept to pursue for a pilot plant, and this committee did not evaluate different concepts. Since both technical performance and economic attractiveness are major considerations for a pilot plant, a parallel approach in the development of more than one fusion concept, at least to the preliminary design level, is appropriate. A key element in the successful Commercial Orbital Transportation Services (COTS) program was the competition between companies. That spirit of competition to develop the most viable pilot plant is appropriate. While specifying the precise number of pilot plant teams is premature, two to four design teams can be envisioned to encourage competition.

Conclusion: To meet the challenge of operating a pilot plant between 2035 and 2040, the development of fusion concepts, technology, and pilot plant designs will need to be performed in parallel.

Parallel development of fusion concepts enables the schedule acceleration required for fusion to be ready as a possible generation alternative as the U.S. transitions to low-carbon emission electricity. Such an approach, however, enables schedule acceleration and is needed for fusion to be ready as a possible generation alternative as the mix in the U.S. transition to low-carbon emission. Parallel development, however, includes inherent risk where some lines of research may not be successful and additional resources will be needed to accomplish multiple lines of activity at the same time as compared to completing activities sequentially. Using the 2019 *Burning Plasma* report as an example, additional resources will be required for the pilot plant and to complete the necessary research and development identified in that report.

Six phases have been identified in the development and operation of a fusion pilot plant: (1) conceptual and preliminary design, (2) final design and construction, (3) start of operation, (4) first phase of operation, (5) second phase of operation, and (6) third phase of operation to take advantage of this unique facility. The scope of these phases is described below. The accompanying timeline illustrates when the various phases need to be implemented to commission a pilot plant into operation sometime between 2035-2040. Detailed planning and resource allocation would be required to develop a more accurate timeline. A timeline with the major elements is shown in Figure 5.1.

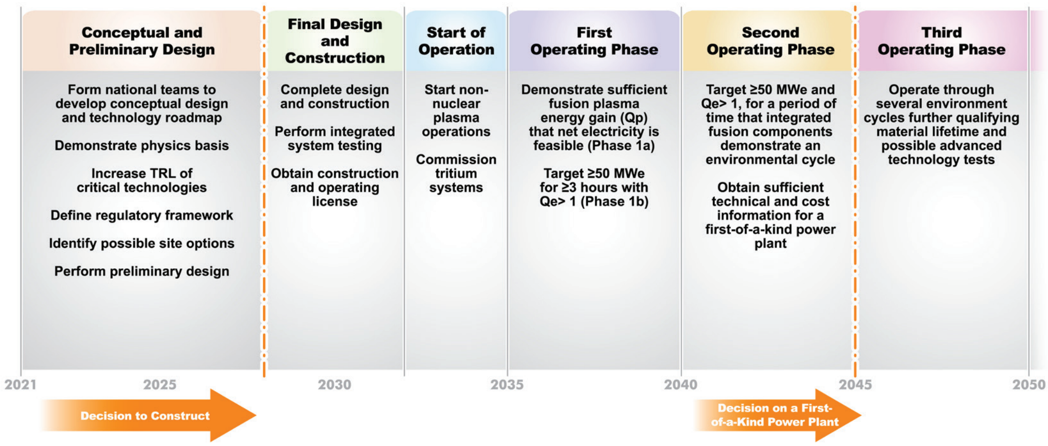

FIGURE 5.1 The phases of operation are illustrated. Chapter 3 defines the key technical goals for the phases in detail. The major goals are shown here and described below.

PRIOR TO START OF CONSTRUCTION: CONCEPTUAL AND PRELIMINARY DESIGN (2021-2028)

The highly integrated nature of a pilot plant requires that both scientific and technical issues are comprehensively addressed. The goal of a lower cost pilot plant relies on innovations in science and technology. These must be performed and extensively evaluated prior to finalizing the design and initiating construction.

While substantial progress has occurred in achieving plasma parameters that may extrapolate to that needed for a pilot plant, outstanding technical issues remain for even the most mature fusion concepts. As discussed in the CPP report, the remaining gaps, which are significant, must be addressed to have confidence in the performance of a pilot plant.

> **Conclusion:** Each successful pilot plant fusion concept must demonstrate that the requisite Lawson parameter to extrapolate fusion plasma gain, particle and energy confinement time, heat exhaust, stability, energetic particle confinement and sustainment, can be achieved with small extrapolation to the parameters needed for a pilot plant to provide confidence in the performance of the pilot plant.

The physics parameters required for evaluating a fusion concept for a pilot plant are broadly discussed in Chapters 3 and 4. The parameters depend in detail on the fusion concept under consideration. These will need to be defined early in this phase to ensure that the experimental and theoretical program supports the timely evaluation of the concept, and selection of these parameters must be made prior to making the decision to start construction.

As noted in the CPP report and discussed further in Chapter 4, many technological issues are at a low technology readiness level (TRL) level, and the maturity of many of the technologies required for the pilot plant needs to increase. Furthermore, to improve the economic attractiveness, there is also a need for technological innovations. This was also highlighted in the FESAC Report on Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy,[3] which identified opportunities for technological innovation. Some of these are already being pursued by the fusion industry as well as by universities and national laboratories.

Conclusion: Critical technologies—such as large-bore, high-temperature superconducting magnets, blanket concepts, functional materials, plasma-facing materials, and tritium processing (including the development of low inventory systems)—have to increase in TRL to 6 or 7 to minimize the scale up to a pilot plant.

While the development of some technologies will facilitate many different fusion concepts, some fusion concepts require specific technologies to meet the goals identified in Chapter 3. It is necessary to increase the maturity of critical technologies that have the largest impact on many different concepts while recognizing that the list of critical technologies may evolve as the design of the pilot plant evolves, for example through the conceptual design phase or as breakthrough developments occur. To illustrate this, most fusion concepts rely on deuterium-tritium (D-T) fuel, and development of blanket concepts to breed tritium and process tritium as described in Chapter 4 is needed. The use of hydrogen and boron, pure deuterium, or deuterium and helium-3 as the fuel would not require tritium breeding; however, a breakthrough in the plasma confinement and temperature is required and other technologies would have to be developed.

The regulatory framework required to obtain a construction and operations license is very important to develop an understanding of the cost and schedule for the pilot plant and eventually a first-of-a-kind (FOAK) power plant. This is discussed in more detail in Chapter 3.

Conclusion: The regulatory framework for fusion should be well defined based on a risk-based approach appropriate to fusion.

The site of a pilot plant has important practical ramifications including public acceptance that can affect the cost and schedule as discussed in Chapter 3.

Conclusion: Site requirements and possible options for site selection will need to be identified.

A fusion pilot plant entails the integration of scientific, engineering, and regulatory issues and requires a broad spectrum of skills.

Finding: Due to the highly integrated aspects of a pilot plant, national well-coordinated teams composed of developers; manufacturers; engineering, procurement and construction (EPC) companies; universities; and national laboratories are needed to develop pilot plant concepts to ensure a robust engineering design and a reliable cost and schedule.

Recommendation: The Department of Energy should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps and lead to an engineering design of a pilot plant that will bring fusion to commercial viability.

Without a design and the resolution of the remaining scientific and technical issues, it is not possible to reliably project the cost of the pilot plant at this time. However, in light of the eventual marketplace for a power plant, the cost of building a pilot plant is an important consideration as well as the projected cost of electricity for a power plant.

Conclusion: If the pilot plant cannot be built for less than the projected cost of the FOAK power plant or the concept does not have the potential for producing electricity at an economically competitive cost, then further innovations will be required to reduce the cost and improve the concept prior to proceeding to construction.

A distinguishing feature of a pilot plant relative to a research project is that it must not only meet scientific and engineering objectives but also provide a cost basis for a FOAK power plant. Thus, the cost of the facility in relation to other projects generating electricity is an important consideration as well as the implications for producing electricity. Delays in meeting this goal would result in decreased opportunities for impacting the U.S. marketplace during the transition to low-carbon emission. On a longer timeline, opportunities to replace the fleet of generating equipment with fusion power plants would exist as well as potentially addressing the needs of the international marketplace due to the expected need for increased low-carbon and non-carbon emission electricity generation as discussed in Chapter 2. This longer timeline was not explored by the committee but would have ramifications for private investors.

PRIOR TO START OF OPERATION OF A PILOT PLANT: FINAL DESIGN AND CONSTRUCTION (2028-2032)

The success of the final design and construction phase will rely on the effectiveness of the integrated national team, which is assumed to continue into this phase. During this phase detailed engineering final design would be completed. It is assumed that technical risks were reduced during the preceding phase through the construction of prototypes if needed and that this would also be used to qualify vendors.

Conclusion: Design and construction of the pilot plant needs to be completed, and integrated systems testing needs to be performed to commission a facility prior to start of operation of a pilot plant.

Conclusion: A construction and operating license will need to be obtained.

In the preceding chapters, the report identified a set of recommendations and conclusions that imply actions that need to be addressed. These are summarized in Table 5.1 by different phases leading up to the completion of construction. After

TABLE 5.1 Various Activities in Support of the Development of a Fusion Pilot Plant

Recommendation or Innovation Category	Immediate Action	Completed by			
		Conceptual Design	Preliminary Design	Final Design	Construction
Organization and design	Create national teams to initiate design from private sector, universities, and national labs	Complete concept Enhance teams	Select and consolidate team(s) Define cost and schedule	**Execute Fusion Pilot Plant design and construction**	
Technology approach	**Develop technology roadmaps**	Complete conceptual design Refine technology roadmaps	Demonstrate preliminary design and critical technology prototypes	Complete final design	Complete construction
Public-private partnerships (PPP)	**Develop PPP models for fusion and tech development**	Execute PPPs	Refine and expand PPPs		
Data/expertise access	**Provide access to private-sector to ITER data** **Expand industrial access to labs and universities**	Continued data and expertise sharing from labs/universities into private sector. Intellectual property agreements.			

TABLE 5.1 Continued

Recommendation or Innovation Category	Immediate Action	Completed by			
		Conceptual Design	Preliminary Design	Final Design	Construction
Regulatory		**Develop regulatory needs/framework**	**Finalize regulatory framework**	Obtain required licenses	
Site			**Develop site requirements and options**	Develop site	
Workforce	**Define Diversity, Equity, and Inclusion (DEI) plan**	Execute DEI improvement	Improve workforce growth consistent with DEI plan		
Plasma performance	Improve plasma performance and predictive capability		**Demonstrate equivalent Q_p>1**	Evolve and improve projections to $Q_p > 1$, $Q_e > 1$ and required availability	
Actuators		Define actuator needs	**Develop actuator technology**	Design and deploy actuators	
Heat exhaust		Define heat exhaust challenge	**Demonstrate heat exhaust solutions**	Implement solutions	
Tritium/fuel cycle		Define tritium/fuel cycle requirements Design demonstration	**Demonstrate tritium/fuel cycle process technology**		Demonstrate efficient tritium/fuel cycle processing
Blanket		Define blanket and test facility requirements Design blanket test facility	**Operate blanket test facility** **Obtain data**	Finalize design and build 1st generation	
Neutron material degradation		Design limited volume neutron source	**Operate neutron source, obtain initial results**	Acquire further data Confirm material and design	
Structural design requirements		**Develop high temperature structural design requirements**	Obtain requisite data	Implement requirements	
Plasma-facing components (PFCs)		Define PFC requirements	**Design and test PFCs**	Fabricate and install PFC	
Blackstart		Evaluate blackstart capability			

NOTE: Summaries of recommendations and conclusions of this report are in red boldface.

the creation of the national teams, design work and technology roadmaps would be developed for each concept to provide a more detailed schedule. Depending on the concept, some elements would receive greater or lesser emphasis. The elements are not organized in priority order.

START OF OPERATION (2032-2035)

Operations would proceed from non-nuclear operations and demonstrate the resolution of scientific and technical issues. For facilities using tritium, the tritium fueling systems would be commissioned.

FIRST PHASE OF PILOT PLANT OPERATION (COMPLETED BY 2035-2040)

Operations would proceed from non-nuclear operations to the use of the fuel mix that will be used in the FOAK fusion power plant and demonstrate fusion power production. For the concepts that will use D-T fuel, the performance of the tritium fuel system would be demonstrated, tritium breeding would be evaluated, and tritium breeding performance would be projected to the Second Phase. A more extensive definition of the goals for the first and second phase of the pilot plant is given in Chapter 3.

Conclusion: Sufficient fusion plasma energy gain (Qp) will need to be demonstrated to show that net electricity is feasible (Phase 1a).

Conclusion: A peak ≥50 MWe net electricity production for ≥3 hours with Qe > 1 (Phase 1b) should be targeted.

Conclusion: Safe and environmentally acceptable operation consistent with the operating license will need to be demonstrated.

SECOND PHASE OF PILOT PLANT OPERATION (COMPLETED BY 2040-2045)

The purpose of this phase is to resolve the scientific and technical issues and enable the fusion industry developers and power plant owners and operators to evaluate both the cost of a FOAK power plant as well as project the cost of producing electricity. In addition to producing net electricity with high availability, the pilot plant would need to demonstrate ability to maintain and replace in-vessel and blanket components, tritium breeding to be >0.9 for concept using D-T and have sufficient data to project the performance of a FOAK, and test materials to 2-3 MW-year m^{-2}. The availability of the plant during this phase should exceed

50 percent and be sufficient to enable projection of the availability and reliability of a FOAK reactor. During this phase, tritium breeding should be demonstrated to be sufficient for a FOAK reactor.

Conclusion: The second phase of a pilot plant should demonstrate peak 50-100 MWe net electricity production and average net electricity generated for at least one environmental cycle, which includes the outage to perform maintenance and replacement of in-vessel components.

THIRD PHASE OF PILOT PLANT OPERATION

The pilot plant may be a viable test bed for materials testing and exploring new technologies to further improve the concept. While the second phase of operation will enable evaluation of structural materials to 2-3 MW-year m^{-2}, the materials may perform beyond that level and qualification of materials can be performed in the pilot plant. Furthermore, other more advanced materials can be tested. This also can be a test bed for alternative blanket designs or coolant systems. The scope of this operating phase requires careful consideration. There is clearly a unique capability that can be exploited; however, this may entail making the pilot plant design more flexible and incorporating this capability at the front end. In general, this complicates the design, increases capital cost for construction, and results in longer construction duration schedules.

Conclusion: The full scope of the third phase should be evaluated as part of the preliminary design effort.

STRATEGIC RISKS AND OPPORTUNITIES

The schedule noted in this plan has both opportunities and risks associated with it. The opportunities include engagement by a recently emerged and growing private industry. As noted earlier, private industry brings both financial resources and a market focus. If anything, its market focus involves an even more accelerated timeline. The schedule provides an opportunity to contribute to supporting the transition to a low-carbon emission electrical marketplace. Due to the level of technological readiness, there are risks in meeting this schedule. They are addressed by identifying the key technical goals and will require resources to tackle them. This ambitious plan requires the performance of research and development in parallel with design. This encourages synergy between the design and research and development effort; however, it does introduce risk that the design will have to be modified or even discarded. A key element in the plan is that each concept design activity develops a technology roadmap to address the critical development requirements. While the recent 2020 CPP and FESAC reports have identified the broad issues, these technology roadmaps will provide a greater level of detail and focus on the advances required for each particular conceptual design strategy. There is also a risk that some of the research development effort will identify that the key goals either cannot be met or result in significant schedule delay; this should not be considered a failure but the result of a healthy, diverse approach to a difficult, integrated design. This issue is addressed by a critical decision point prior to proceeding with construction. While the indicated timeline for the design and construction of pilot plant is less than that of constructing JT-60SA, W7-X, and ITER, it is worth noting that it is longer than for JET and TFTR. The design effort including prototypes of key components will be critical to develop the construction and assembly schedule.

The duration of the operating phase prior to fusion power performance is short relative to what JET and TFTR needed to develop new plasma operating scenarios and commission the tritium and remote handling systems. In this plan, the plasma operating scenario will be demonstrated in experiments that operate with equivalent fusion gains greater than unity prior to the decision to construct. This experience will be invaluable to the pilot plant. Of course, new technologies such as the tritium breeding blankets on the pilot plant will have to be tested and developed, but the prior development on test stands will increase the likelihood of their performance. Since a volumetric neutron source may not be available in time to fully qualify neutron degradation in structural and functional materials, phase three pilot plant operation would fulfill this and assess component lifetime. All risks can never be fully mitigated; however, the major technological issues have been identified in this report.

There are risks and opportunities associated with changes in the timeline for the transition to a low-carbon emission electrical marketplace. Due to climate change considerations, the transition may accelerate. This will make it more difficult for fusion to contribute. This motivated, in part, the recommendation for the fusion program increasing its engagement with the energy community. Due to other political or technological considerations, the transition may be delayed. This may be an opportunity for fusion to make a greater contribution if the proposed timeline is followed.

The risks associated with the proposed timeline were considered in the context of the risks of extending the timeline to a pilot plant. The following are some ramifications of an extended timeline or even elimination of the timeline. First and foremost, the transition to low-carbon emission electricity generation is under way. The electrical utilities will use whatever combination of technologies are available to make the transition. Without firm low-carbon and non-carbon emission electricity generators, the the price of electricity will increase. Fusion has the potential to contribute to addressing these electricity price concerns. Since power plants typically operate for 40 years or more, a delayed timeline will diminish opportunities for fusion to enter the marketplace. By entering the marketplace, it will be possible to refine and improve fusion commercial power plants. Without entering the marketplace, that process of innovation will be hampered. Second, a schedule that does not address the needs of the marketplace or is very long term will discourage private investment and retention of expertise in U.S. industry. Third, China and the United Kingdom are embarking on development to be the first to put fusion on the grid. The United States has played a major role in the development of the fundamental science underlying fusion and has the opportunity to build on its past accomplishments or it can let other countries take the lead on this technology.

The committee acknowledges there are risks and opportunities with the proposed timeline, which were considered in the context of an extended timeline. In addition to the scientific risks of generating fusion power for extended durations and the technical risks of advanced materials and engineering systems to close the fuel cycle in a concept that is cost effective, a major risk is whether the timely resources required from the public and private investors to move forward will become available.

SUMMARY

In response to the statement of task, the committee has in Chapter 2 identified the key requirements for fusion to support the transition to a low-carbon emission electrical marketplace by 2050. A pilot plant is a necessary step in the development of fusion energy. This report identifies the technical and economic considerations that need to be addressed for fusion to make an impact on the marketplace.

The key marketplace requirements combined with the previous technical studies provided a basis for identifying the key goals for fusion in Chapter 3. This was a broad perspective ranging from demonstrating scientific and technical feasibility to defining the performance goals for a fusion pilot plant. In support of the key goals in Chapter 3, the scientific and technical innovations required to both demonstrate feasibility and address the cost requirements of the marketplace were presented in Chapter 4. Fusion development will require participation by industry, including companies developing fusion energy, building components and providing EPC services, national laboratories, and universities bringing together a broad range of skills. A key element in Chapter 4 is the role of public-private partnerships to potentially accelerate the development of fusion and to ensure a transition to the marketplace. In this chapter, an accelerated timeline to build and operate a pilot plant to enable fusion to support the transition in the electrical marketplace is presented.

Conclusion: Successful operation of a pilot plant in the 2035-2040 timeframe requires urgent investments by DOE and private industry—both to resolve the remaining technical and scientific issues and to design, construct, and commission a pilot plant.

NOTES

1. S. Baalrud, N. Ferraro, L. Garrison, N. Howard, C. Kuranz, J. Sarff, and W. Solomon, 2020, "A Community Plan for Fusion Energy and Discovery Science," https://arxiv.org/abs/2011.04806.
2. National Academies of Sciences, Engineering, and Medicine, 2019, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25331.
3. Fusion Energy Sciences Advisory Committee, 2018, "Fusion Energy Sciences Advisory Committee Report: Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy," updated February 15, https://science.osti.gov/-/media/fes/fesac/pdf/2018/TEC_Report_15Feb2018.pdf.

Appendixes

A

Statement of Task

The committee will be charged with providing guidance to the U.S. Department of Energy, and others, that are aligned with the objective of constructing a pilot plant in the United States that produces electricity from fusion at the lowest possible capital cost ("Pilot Plant"). In the study, to be completed within 8 months of project initiation, the committee shall provide a concise report that addresses the following points:

- In developing and carrying out a plan for building a Pilot Plant, key goals need to be established for all critical aspects of the Pilot Plant. Identify those key goals, independent of confinement concept, which a Pilot Plant must demonstrate during each of its anticipated phases of operation.
- List the principal innovations needed for the private sector to address, perhaps in concert with efforts by DOE, to meet the key goals identified in the first bullet.

CONSIDERATIONS

In addressing the first bullet in the statement of task, the committee should consider the key goals for each of the plant's anticipated phases of operation. Areas for key goals that the committee might consider include scientific (e.g., materials and systems performance and integration), technical (e.g., electrical output and availability), economic (e.g., capital costs and time frame, operating and maintenance costs), environmental (e.g., level of radioactive wastes), and safety-related (e.g., regulatory, tritium inventory).

In carrying out the statement of task, the committee is encouraged to seek input from potential "future owners" of power plants, such as electric utility companies, and potential manufacturers of fusion power plant components, to broadly characterize the energy market for fusion and to provide input on what they would look for in a fusion pilot plant and how such plants can contribute to national energy needs.

B

Biographies of Committee Members

RICHARD J. HAWRYLUK, *Chair,* is associate director for fusion at the Princeton Plasma Physics Laboratory (PPPL). Among other responsibilities, he was interim deputy director for operations from October 2018 to January 2019 and interim project director of the NSTX-U Recovery Project from March 2018 to July 2019. From August 2017 to July 2018, he was interim director of PPPL. Dr. Hawryluk came to the lab in 1974 after receiving a Ph.D. in physics from the Massachusetts Institute of Technology (MIT). He headed the Tokamak Fusion Test Reactor at PPPL, then the largest magnetic confinement fusion facility in the United States, from 1991 to 1997, and led the deuterium-tritium experiments. Dr. Hawryluk oversaw all research and technical operations as deputy director of the laboratory from 1997 to 2008. He then spent several years working on research and management topics associated with ITER, as head of the ITER and Tokamaks Department from 2009 to 2011 and from 2013 to 2016, and as deputy director general for the Administration Department of ITER from 2011 to 2013. He also chairs the board of editors of *Nuclear Fusion*, a monthly journal devoted to controlled fusion energy. He has chaired and participated in numerous national and international program reviews and advisory committees.

BRENDA L. GARCIA-DIAZ is the manager for the Energy Materials Group at Savannah River National Laboratories (SRNL). She leads a strategic initiative project to develop electrochemical fluorination for used nuclear fuel reprocessing and was recently the program manager on nuclear material storage programs looking at corrosion and degradation in nuclear material storage containers before her current position at SRNL. Prior to that, Dr. Garcia-Diaz was a co-founder and CEO of Greenway Energy, a company focused on Clean Energy Research that has received multiple commercial and Department of Energy (DOE)-funded projects. A Puerto Rico native, she received her master's degree in chemical engineering from the University of Puerto Rico, Mayagüez, and Ph.D. in chemical engineering from the University of South Carolina. Dr. Garcia-Diaz is the co-author on more than 10 patent disclosures and applications.

GERALD L. KULCINSKI is the Grainger Professor of Nuclear Engineering (emeritus) at the University of Wisconsin, Madison, where he was the director of the Fusion Technology Institute from 1974 to 2018. Dr. Kulcinski was the associate dean of research for the College of Engineering from 2001 to 2014. He was elected to the National Academy of Engineering in 1993 and was awarded the NASA Public Service Medal in 1993 and the NASA Exceptional Public Service Medal in 2010. He served on the NASA Advisory Council from 2005 to 2009 and on the Advisory Committee for the Department of Commerce on Emerging Technology from 2008 to 2018. He has been a fellow in the American Nuclear Society (ANS) since 1978. He has served as a chair, co-chair, or member of six study committees.

KATHRYN A. McCARTHY is the associate laboratory director for Fusion and Fission Energy and Science at Oak Ridge National Laboratory. From January 2017 to February 2020, Dr. McCarthy was vice president of research and development and laboratory director at the Canadian Nuclear Laboratories. She was the national technical director for systems analysis for the DOE-NE Fuel Cycle R&D Program, preceded by involvement in various other nuclear fission and fusion programs. Dr. McCarthy was a guest scientist at the Kernforschungszentrum in Germany, March-September 1989, and participated in the DOE U.S./U.S.S.R. Young Scientist Program at the Efremov and Kurchatov Institutes in Russia, and the Latvian Academy of Science in Latvia, September 1989-August 1990. Her awards include an ANS Presidential citation in 2015 for "Leadership and guidance of the Light Water Reactor Sustainability effort . . . that has helped set the stage for U.S. power companies to be able to make informed decisions regarding subsequent license renewal for their operating nuclear units," and in 2007 for "outstanding service to the ANS," the 2000 ANS Women's Achievement Award, 1996 International Thermonuclear Experimental Reactor U.S. Home Team Leadership Award, and the 1994 David Rose Award for Excellence in Fusion Engineering. She received her B.S. in nuclear engineering at the University of Arizona; and M.S and Ph.D. in nuclear engineering at University of California, Los Angeles. She is a member of the National Academy of Engineering and served on the Committee on the Prospects for Inertial Fusion Energy in 2013.

PER F. PETERSON holds the William and Jean McCallum Floyd Chair in the Department of Nuclear Engineering at the University of California, Berkeley. He is also chief nuclear officer for Kairos Power, where he guides nuclear technology review and advises on scientific and technical topics for KP-FHR (Kairos Power fluoride salt-cooled high-temperature reactor) technology development and licensing. At University of California, Berkeley, he performs research related to high-temperature fission energy systems, as well as topics related to fusion energy technologies and the safety and security of nuclear materials and waste management. He has served as a member or chair of numerous advisory committees for the national laboratories and National Academies. His research in the 1990s contributed to the development of the passive safety systems used in the GE ESBWR (Economic Simplified Boiling Water Reactor) and Westinghouse AP-1000 reactor designs. His 2003 *Nuclear Technology* article with Charles Forsberg and Paul Pickard identified salt-cooled, solid-fuel reactors as a promising technology, today called fluoride-salt-cooled, high-temperature reactors (FHRs). His current work and research focuses on enabling and accelerating advanced nuclear energy technologies.

JEFFREY P. QUINTENZ recently retired from General Atomics (GA) where he was senior vice president of the Energy Group and is now a part-time employee of TechSource, Inc., with the title of senior nuclear subject matter expert. At GA, Dr. Quintenz led research and development divisions encompassing all GA activities in magnetic fusion energy, inertial confinement fusion (ICF), and nuclear technologies and materials (fission). His research interests include fusion (both inertial and magnetic confinement), nuclear power, and nuclear weapons deterrence. Previously Dr. Quintenz was director of pulsed power sciences and ICF program manager at Sandia National Laboratories. After joining Sandia, he developed and applied computational tools to the study of plasmas and particle beams. He has also served as director of the ICF Office within the National Nuclear Security Administration (NNSA), and president of Lockheed Martin Nevada Technologies with responsibility for the stockpile stewardship program activities at the Nevada Test Site. He is a fellow of the Institute for Electrical and Electronics Engineers (IEEE) and recipient of the NNSA Excellence Medal. He earned his Ph.D. in electrical engineering from the University of Arizona. He is currently a member of the Defense Programs Advisory Committee serving the senior leadership in the NNSA.

WANDA K. REDER is currently the president and CEO of Grid-X Partners based in Chicago. Prior to that, she was the chief strategy officer at S&C Electric Company. Her pioneering work has led to smart grid deployments and wind, solar energy, and utility-scale battery storage integration into traditional utility systems. An IEEE Fellow, Dr. Reder was recognized with the 2014 IEEE Richard M. Emerson Award for her leadership in the IEEE Smart Grid program and in the continued growth of the Power and Energy Society (PES), including the creation of its Scholarship Fund program. She was the first woman president of PES and is responsible for the launch of the IEEE Smart Grid, positioning IEEE as the leading source for information on smart-grid technology. Dr. Reder is a member of DOE's Electricity Advisory Committee. She is also a member of the National Academy of Engineering and was a candidate for 2017 IEEE President-Elect.

DAVID W. ROOP is the principal consultant at DWR Associates. He has a 43-year career in the electric utility industry focused on electric transmission and substation operations and management. He previously chaired Dominion Energy Virginia's resiliency strategy team resulting in industry leading initiatives. These initiatives include the development and implementation of large power transformers hardened against geomagnetically induced currents, implementation of substation security initiatives, electromagnetic pulse hardening of substations, and the development of transmission mobile equipment such as Static Synchronous Compensators (STATCOMs). In addition, Mr. Roop has managed the rapid deployment of eight Flexible AC Transmission Systems (FACTS) across Dominion Energy Virginia's system, which includes static var compensators and STATCOMs. His duties included technical support and engineering resources for electrical equipment, protective relays, and operations including research activities to support Transmission System development. His organization also provided technical support for Dominion Generation substations, including protective relaying, for both regulated and merchant plants. He holds one patent for grounding of electrical systems. Currently, he is a registered professional engineer in the Commonwealth of Virginia and is an active member of CIGRE presently serving as president of the CIGRE U.S. National Committee. He was elected to the National Academy of Engineering in 2018 and currently serves on the board of directors of the Virginia Academy of Science, Engineering, and Medicine. Mr. Roop is a life member of the IEEE and member of Eta Kappa Nu. Mr. Roop is also an adjunct professor of practice at Virginia Tech in the Bradley Department of Electrical and Computer Engineering.

PHILIP SNYDER is director of the Theory and Computational Science Department at General Atomics in San Diego, California. He received a B.S. in computational physics from Yale University (1993) and a Ph.D. in plasma physics from Princeton University (1999) before joining the fusion theory group at General Atomics. His research has focused on electromagnetic plasma turbulence and on the stability and dynamics of the edge region of magnetic fusion plasmas, particularly the physics of the edge transport barrier ("pedestal") and edge localized modes. He developed a predictive model of the pedestal, which has been coupled to models of the core plasma to predict and optimize performance of existing and future fusion devices.

He serves as principal investigator for the Theory and Simulation of Fusion Plasmas and the Edge Simulation Laboratory projects. He is a fellow of the American Physical Society (APS) (2010) and a recipient of the APS John Dawson Award for Excellence in Plasma Physics Research (2013) and the International Atomic Energy Agency (IAEA) Nuclear Fusion Prize (2014). He served as a member of the National Academies Committee on a Strategic Plan for U.S. Burning Plasma Research.

JENNIFER L. UHLE is the Nuclear Energy Institute's (NEI's) vice president of generation and suppliers. Prior to joining NEI, Dr. Uhle served as the director of reactor safety programs at Jensen Hughes, a consulting company to the nuclear industry. Dr. Uhle joined Jensen Hughes in 2016, working in advanced reactors, thermal-hydraulics, and regulatory affairs. Previously, she served at the U.S. Nuclear Regulatory Commission for 23 years in several positions including the deputy director of the offices of Nuclear Regulatory Research and Nuclear Reactor Regulation and the director of the Office of New Reactors. Dr. Uhle obtained her bachelor's and doctorate degrees in nuclear engineering from MIT in 1991 and 1996, respectively, with a specialization in reactor systems and design. She served as the U.S. representative to the International Atomic Energy Agency's first fact-finding mission to Fukushima in 2011. She serves on the advisory committee to MIT's Department of Nuclear Engineering.

DENNIS G. WHYTE is the Hitachi America Professor of Engineering at MIT, a professor in the MIT Department of Nuclear Science and Engineering, and director of the MIT Plasma Science and Fusion Center. Dr. Whyte's research interests focus on accelerating the development of magnetic fusion energy systems. He has led teams and published more than 300 papers across the multidisciplinary fields of magnetic fusion including plasma confinement, plasma-surface interactions, blanket technology, plasma diagnostics, superconducting magnets, and ion beam surface analysis. Dr. Whyte leads the overall MIT research team on SPARC, a private sector–funded compact high-field tokamak presently under development to demonstrate net fusion plasma energy gain. He also leads the Laboratory for Innovations in Fusion Technology at the Plasma Science and Fusion Center, which has energy company sponsorship to explore early-stage, disruptive fusion technologies. As an educator, Dr. Whyte has been deeply involved in student design courses for fusion energy systems. He was educated in Canada, gaining his Ph.D. from the University of Quebec working on the Tokamak de Varennes, Canada's national fusion facility. He previously worked at the DIII-D National Fusion facility for a decade and served as a senior lecturer at University of California, San Diego. He was an assistant professor in the Nuclear Engineering department at the University of Wisconsin, Madison from 2002 to 2006. Dr. Whyte previously served as MIT Nuclear Science and Engineering Department head. He has served as leader of the

Boundary-Plasma Interface Topical Group of the U.S. Burning Plasma Organization and is a fellow of the APS Division of Plasma Physics. He was awarded DOE's Plasma Physics Junior Faculty Award in 2003. In 2013, he won the IAEA Nuclear Fusion Prize and was presented the Fusion Power Associates Leadership Award in 2018. He is a two-time winner of the Ruth and Joel Spira Award for Distinguished Teaching from the School of Engineering at MIT. Dr. Whyte has been a committee member on two previous National Academies' studies: "A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program" (2009) and "An Assessment of the Prospects for Inertial Fusion Energy" (2013).

BRIAN D. WIRTH is the Governor's Chair Professor of Computational Nuclear Engineering in the Department of Nuclear Engineering at the University of Tennessee, Knoxville, and Oak Ridge National Laboratory. Dr. Wirth's research investigates the performance of nuclear fuels, structural materials, and plasma-facing components in nuclear environments, utilizing computational materials modeling complemented by experimental investigation. Dr. Wirth received a B.S. in nuclear engineering from the Georgia Institute of Technology in 1992 and a Ph.D. in mechanical engineering from the University of California, Santa Barbara, in 1998. Dr. Wirth spent 4 years in the High Performance Computational Materials Science Group at Lawrence Livermore National Laboratory. In 2002 he joined the faculty at the University of California, Berkeley, as an assistant professor of nuclear engineering and was promoted to associate professor in 2006. He has received a number of awards, including the 2014 DOE Ernest O. Lawrence Award in Energy Science and Innovation, the 2016 Mishima Award from the ANS for outstanding work in nuclear fuels and materials research, and the 2003 Presidential Early Career Award for Scientists and Engineers. Dr. Wirth is a fellow of the American Association for the Advancement of Science (2016 Fellow, Physics Section) and the ANS (2017 Fellow).

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Committee Meeting Agendas

MEETING 1

Day 1: August 26, 2020

CLOSED SESSION

11:00 AM Welcome, Introductions, and Meeting Overview
Introductions, Study Process, Bias and Conflict Discussion
Committee Composition and Balance Discussion
Discussion: Statement of Task

OPEN PUBLIC SESSION

2:45 Discussion with DOE-FES Sponsor
Jim Van Dam, DOE-FES

CLOSED SESSION

4:30 Wrap up discussion, possible outline, and strategy going forward

Day 2: September 2, 2020

CLOSED SESSION

11:00 AM Recap of previous day
Discussion of the charge to the committee, and end goals

OPEN PUBLIC SESSION
12:00 PM Discussion with DOE-OS
Chris Fall, DOE-OS

12:30 Discussion with ARPA-E
Scott Hsu, ARPA-E

1:00 Break

1:30 Discussion with Hill staff
Adam Rosenberg, House Science Committee
Hillary O'Brian, House Science Committee

2:00 Discussion of the previous Burning Plasma Report
Mike Mauel, Burning Plasma Report Chair

CLOSED SESSION
3:00 Roundtable discussion of previous
Discussion of the possible outline
Wrap up discussion
Planning next meetings and assignments

6:00 Adjourn

MEETING 2

Day 1: September 23, 2020

CLOSED SESSION
11:00 AM Committee Discussion

OPEN PUBLIC SESSION
11:15 Discussion with Panel 1: Licensing
Marc Nichol, Nuclear Energy Institute
Bill Reckley, Nuclear Regulatory Commission
Gary Becker, NuScale Power, LLC

12:45 PM Break

1:30 Discussion with Panel 2: Power Plant Owner/Operator Interest
Brad Adams, Southern Nuclear Company
Ralph Izzo, Public Service Enterprise Group
Tina Taylor, Electric Power Research Institute

3:00 Break

4:00 Discussion with Panel 3: Developers of Fusion Power Plants
Michl Binderbauer, TAE Technologies
Mike Delage, General Fusion
Andrew Holland, Fusion Industry Association
David Kingham, Tokamak Energy
Bob Mumgaard, Commonwealth Fusion Systems
Brian Nelson, Zap Energy Inc.

5:30 Adjourn for the day

Day 2: September 24, 2020

CLOSED SESSION
4:00 PM Draft F&R discussion for Chapter 2 and 3
Comments on draft introductions
Plan forward, timing of next post-meeting closed session

6:00 Adjourn

Day 3: October 7, 2020

CLOSED SESSION
11:00 AM Committee Discussion

OPEN PUBLIC SESSION
11:30 Discussion with Panel 1: Universities
Saskia Mordijck, College of William and Mary
Jean Paul Allain, Pennsylvania State University
John S. Sarff, University of Wisconsin, Madison
George R. Tynan, University of California, San Diego

1:30 PM Discussion with Panel 2: Component Manufacturers
Muhammad Fahmy, Bechtel Power Corporation
Alexander Molodyk, S-Innovations
Bill Shingler, Fluor Government Group
Tony S. Taylor, General Atomics

3:30 Discussion with Panel 3: National Laboratories
Dave Babineau, Savannah River National Laboratory
Steven C. Cowley, Princeton Plasma Physics Laboratory
Corey McDaniel, Canadian Nuclear Laboratories
Mickey R. Wade, General Atomics

CLOSED SESSION
5:00 Panel Recap

6:00 Adjourn for the day