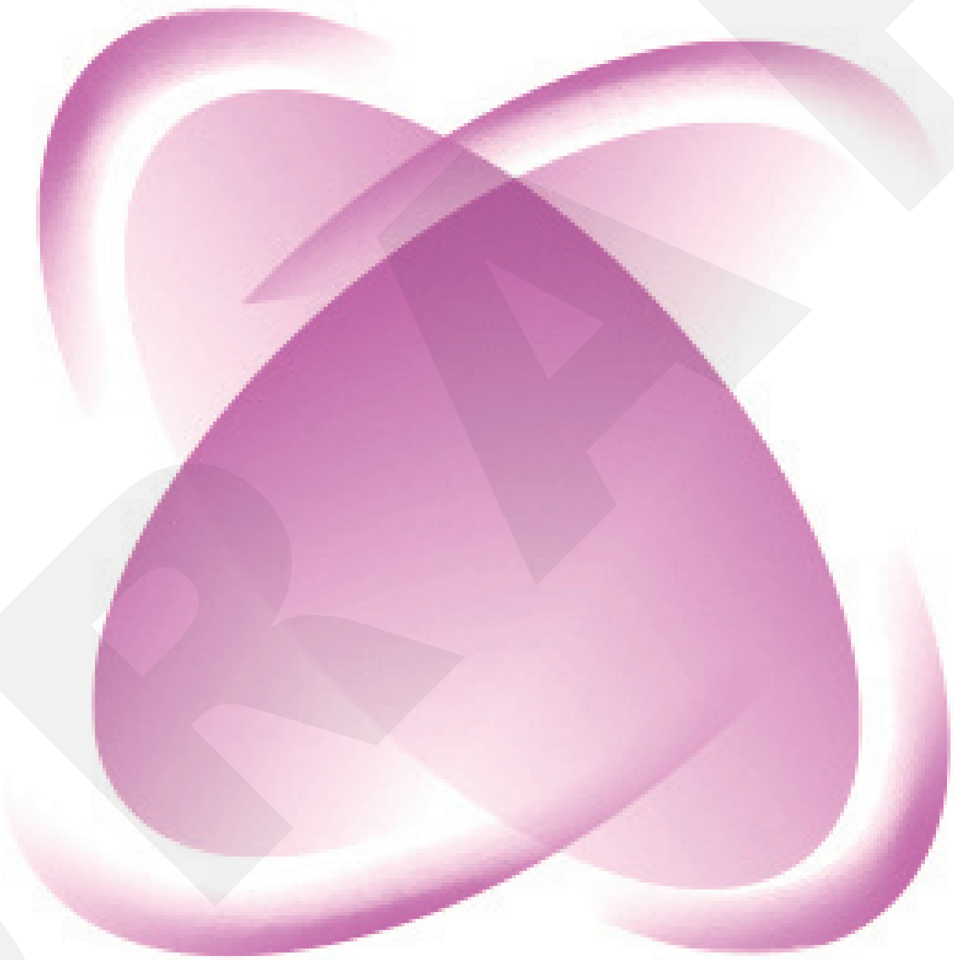
A long-range plan to deliver fusion energy and to advance plasma science

Powering the Future
Fusion & Plasmas



A Report of the Fusion Energy Sciences Advisory Committee

2020

The production of this report was sponsored by the US Department of Energy, Office of Science, Fusion Energy Sciences in the year 2020.

This report provides a decade-long vision for the field of fusion energy and plasma science, presenting a path to a promising future of new scientific discoveries, industrial applications, and ultimately the timely delivery of fusion energy. We identify critical areas for research and development and prioritize investments to maximize impact. The research community worked hard over a year-long-process to convey a wealth of creative ideas and its passion to accelerate fusion energy development and advance plasma science. Their effort culminated in the consensus Community Planning Process report. Our work is based heavily on this report, and we extend our sincere gratitude to our colleagues for their efforts. Following the research community's lead, we worked by consensus in generating this report. Different ideas were listened to and were thoughtfully deliberated until a shared view on each issue emerged. This process allowed us to discuss and appreciate our different points of view and come to consensus language. Ultimately, we speak with one voice in conveying a vision for a vibrant program that will bring significant benefit to society.

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Fusion—the merging of nuclei to release the energy that powers stars—and plasmas—ionized gas, the fourth state of matter that makes up stars—are inextricably linked. Their shared history exemplifies how basic scientific research translates from a deeper understanding of the universe to technologies that benefit society.

Now is the time to move aggressively toward the deployment of fusion energy, which could substantially power modern society while mitigating climate change. Scientific and technological innovations point the way toward a unique US vision for economically attractive fusion energy, setting the stage to build a fusion pilot plant by the 2040s. The foundation of a US fusion energy industry is central to this vision and this industry has already taken root, with approximately $2 billion of private capital invested to date.

The technological and scientific achievements arising from plasma research are significant and far-reaching. The US vision for fusion energy is enabled by breakthroughs in the physics of magnetically confined plasmas, where record confined pressures have recently been achieved. Plasma physics helps us understand not only the confined plasmas that could power an energy-generating fusion reactor, but distant objects that capture our imagination, such as supernovae and black hole accretion disks. Understanding the exotic states of matter created using the most intense lasers in the world requires deep plasma physics knowledge. Plasmas transform society, enabling the development of industry-changing technologies, including plasma-enabled manufacturing at the heart of the trillion-dollar information technology industry.

Partnerships will accelerate progress. Partnership in the international ITER fusion project is essential for US fusion energy development, as is supporting the continued growth of the private sector fusion energy industry. Public-private partnerships have the potential to reduce the time required to achieve commercially-viable fusion energy. The diversity of topics addressed by plasma science is reflected in the wide range of federal agencies that are committed to supporting its development. Increased coordination among those agencies is warranted to maximize progress in research and development.

Fusion and plasma research in the US are world-leading, and continued scientific leadership requires nurturing and agility. The US is poised to take the lead globally in the development of a private sector fusion energy industry, but this opportunity will be lost without strong support. Similarly, our leadership position in some key research areas is threatened by the absence of investment in major new facilities that address critical gaps in the relevant science and technology.

For the first time, scientists have created a long-range plan to accelerate the development of fusion energy and advance plasma science. Earlier, the community undertook a year-long study that identified new opportunities and developed guidance for prioritization. The consensus that resulted in the Community Planning Process report formed the basis for the strategy detailed here. This plan calls for important redirections in DOE Fusion Energy Sciences research programs and is embodied by six technology and science drivers in two thematic areas.

Fusion Science and Technology

The Fusion Science and Technology area should focus on establishing the scientific and technical basis for a fusion pilot plant by the 2040s:

- Sustain a burning plasma. Build the science and technology required to confine and sustain a burning plasma.
- Engineer for extreme conditions. Develop the materials required to withstand the extreme environment of a fusion reactor.
- Harness fusion power. Engineer the technologies required to breed fusion fuel and to generate electricity in a fusion pilot plant by the 2040s.

Plasma Science and Technology

The Plasma Science and Technology area should focus on new opportunities to advance fundamental understanding, and in turn translate these advances into applications that benefit society:

- Understand the plasma universe. Plasmas permeate the universe and are the heart of the most energetic events we observe.
- Strengthen the foundations. Explore and discover new regimes and exotic states of matter, enabled by new experimental capabilities.
- Create transformative technologies. Unlock the potential of plasmas to transform society.

This plan makes the difficult choices necessary to embark on these critically important directions. A number of recommendations, which express an optimized path to achieve our goals, emerged from this process. Overarching recommendations are made that identify important programmatic changes:

- Addressing the technology and science drivers will require continuing investment in the design, construction and operation of facilities that provide important new capabilities. To allow this, resources need to be established in the program for ongoing investment. Opportunities for developing small and mid-scale facilities aligned with the plan are also needed. Pre-conceptual design toward new experimental facilities should be a part of regular program activities to better prepare for future strategic planning.
- To achieve efficiencies and maximize technical progress across all the elements of this strategic plan, build on the existing successful partnerships with NSF, ARPA-E and NNSA, and explore opportunities to form new partnerships with other agencies and with industry. The successful Innovation Network for Fusion Energy (INFUSE) program should be expanded and new public-private partnership program, including milestone-based cost-share programs, should be developed.
- This long-range planning process should be repeated regularly to enable periodic review and update of the strategic plan with strong community engagement.
- Policy changes should be developed and implemented that improve diversity, equity, and inclusion within the research community and allow discipline-specific workforce development.

The strategic plan is developed through a series of recommendations, not in priority order, on needed programs and experimental facilities:

- A fusion pilot plant design effort should begin immediately to develop cost attractive fusion solutions on the fastest time scale possible.
- The fusion pilot plant goal requires a pivot toward research and development of fusion materials and other needed technology. Emphasis is needed on fusion materials science, plasma facing components, tritium-breeding blanket technology and the tritium fuel cycle. A number of key experimental facilities are recommended. The Fusion Prototypic Neutron Source (FPNS) will provide unique material irradiation capabilities and the Material Plasma Exposure Experiment (MPEX) and High Heat Flux testing experiments will enable solutions for the plasma facing materials. The Blanket Component Test Facility (BCTF) will provide the scientific basis for tritium fuel breeding and processing.
- The successful tokamak plasma confinement concept must be advanced to meet the stringent requirements of a fusion pilot plant. A sustained burning plasma at high power density is required simultaneously with a solution to the power exhaust challenge: mitigating the extreme heat fluxes to materials surrounding the plasma. US partnership in ITER provides access to a high-gain reactor-scale burning fusion plasma and an accompanying US ITER research team and program to exploit this facility must be developed. Present tokamak experiments in the US and abroad can address key issues in the near-term and new opportunities in the private sector should be leveraged and supported. Addressing the core/exhaust integration challenge requires a new tokamak facility, the EXhaust and Confinement Integration Tokamak Experiment (EXCITE).
- The plan embraces the development of innovative ideas that could lead to more commercially attractive fusion systems and address critical gaps with entirely new concepts. The quasi-symmetric stellarator is the leading US approach to develop disruption-free, low-recirculating-power fusion configurations and should be tested experimentally with a new US stellarator facility. Liquid metal plasma facing components have the potential to ameliorate some of the extreme challenges of the plasma-solid interface and may reveal new plasma operating regimes. Inertial fusion energy research can leverage significant investments in the US in order to establish new technologies and approaches toward energy production. Private investment in alternative fusion plasma configurations has enabled breakthroughs that have potential as fusion energy sources. Strengthening these elements will provide both scientific opportunity and programmatic security.

- A sequence of mid-to-large-scale facilities will establish a leadership role in frontier plasma science. To strengthen plasma foundations: the Matter in Extreme Conditions Upgrade (MEC-U) will provide a world-class user facility in high energy density science by co-locating a high intensity (petawatt-class) laser and a long-pulse shock compression laser with the Linac Coherent Light Source free electron laser; and a multi-petawatt laser will push the frontier of laser intensity and reveal fundamental quantum electrodynamic processes of creating matter and plasma directly from light. To understand the plasma universe: a new Solar Wind facility will close key science gaps in plasma turbulence, connecting laboratory experiments with space and astrophysical observations; and a mid-scale Z-pinch facility will allow access to strongly magnetized high energy density matter relevant to astrophysics and fusion energy research.
  To create transformative technologies: A high repetition rate high-intensity laser system will dramatically increase the rate at which high energy density plasma experiments can be conducted, with the potential to significantly advance the development of plasma-based accelerators.

- A plasma-based technology research program will provide the scientific basis needed to enable the next generation of technological inventions. Plasmas can enable transformative technologies in manufacturing, microelectronics, biotechnology, medicine, and aerospace. Fulfilling this potential will require a dedicated and nimble research program able to take advantage of the translational nature of this research by connecting the basic science with the breadth of applications.

- Programs that support foundational plasma science research should be emphasized. Foundational science fosters creative exploration that sets new directions for the field, addresses fundamental questions of nature, and explores novel states of matter.

Our prioritization of needed programs and facilities was applied to address three different funding scenarios: constant level of effort, modest growth (2% yearly growth), and unconstrained, but prioritized.

In the constant level of effort scenario, programs in fusion materials and technology are grown, the MPEX facility is completed and construction of FPNS begins. Important scientific and technical progress continues in other areas. However, US leadership in fusion and plasma science is at risk in this scenario. New activities to address other key gaps are significantly delayed, and many opportunities for innovation and enhanced US leadership cannot be acted upon. To provide needed resources for fusion materials and technology programs and facilities, operations and research programs on existing domestic tokamak facilities, DIII-D and NSTX-U, which aim to address fusion pilot plant design gaps, will have to be modestly reduced in the near term. One domestic tokamak facility will likely need to cease operations mid-decade to free the resources required to make progress on FPNS. A nascent ITER research team is developed and some shift of resources to collaboration with international and private sector facilities is possible. A limited plasma technology program will be established. Almost all other strategically selected enhancements of experimental capabilities and new program activities will be delayed. Importantly, completing the ongoing MEC-U project is not possible. New facility concept studies will be pursued to build a basis for deliberations on these important facilities to be ready for improving budgetary conditions.

The return on the investment of the relatively small increment from the constant level of effort to the modest growth scenario is substantial. Fusion materials and technology research is further strengthened and FPNS is accelerated. Increased focus is given to addressing the core/exhaust integration challenge, such that design and start of construction of the EXCITE facility may be possible. Fundamental plasma research and plasma technology program areas are modestly grown, and networks are established and bolstered. However, substantial risks and missed opportunities remain. A similar reduction of activity on existing tokamak programs as in the constant level of effort scenario is envisioned. Other new major facilities are not possible in this scenario, including MEC-U, leaving important research gaps unaddressed and US leadership opportunities are unfulfilled.

In the unconstrained scenario the complete strategy as summarized above can be implemented, but prioritization and staging of items beyond the constrained scenarios is proposed. Additional investment beyond the modest growth scenario will have significant return. Major scientific advances would be enabled and progress toward realizing practical fusion energy would be accelerated. FPNS would be further accelerated to ensure operations as soon as possible. In addition, a number of additional facilities and program enhancements have been identified that capture the opportunities provided by the full breadth and creativity of the program. Priority order for additional facility investment is expressed thusly: the MEC-U project and the EXCITE facility at equal priority; a new quasi-symmetric stellarator device; the blanket component test facility; the Solar Wind facility; a facility for full-size component-level high heat flux testing; a multi-petawatt laser facility; and, in collaboration with other agencies, the high-repetition rate laser facility and the mid-scale Z-pinch could be pursued. Research programs would be bolstered first to accompany new facility investments.

Chapter 1
Introduction and Overview

Fusion and plasmas: powering the future

The US is at a critical moment in the effort to develop fusion as a carbon-neutral, sustainable source of energy. The last decade has seen significant progress in the physics and engineering necessary to confine high temperature plasmas for fusion, with important technological breakthroughs, including high temperature superconductors, that enable the advances in magnet technology required to achieve that confinement. We are on the verge of entering an era of burning plasmas with the international ITER experiment, set to begin operation this decade. At the same time, there has been rapid growth in privately financed fusion research and development, leading to an emerging fusion energy industry. These developments enable a unique and ambitious path for US fusion research, targeting a low capital cost fusion pilot plant that will form the basis for economically attractive fusion electricity.

Fusion energy and plasmas are inextricably linked. A fusion reactor requires a confined, controlled, burning plasma at its core. For this reason, fusion research has historically been an important driver for the development of plasma physics as a fundamental field. The link between the two fields is strong but does not fully define either one. Fusion energy requires research and development into materials resistant to neutron irradiation, into technologies for breeding fusion fuel and into enabling technologies like magnets. The field of plasma science and engineering is intellectually diverse, highly interdisciplinary, and has myriad applications beyond fusion energy.

Plasma science and engineering has advanced significantly over the last decade and future opportunities abound. Extreme states of matter have been produced and studied using the world's most intense lasers developed using Nobel Prize winning research in chirped pulse amplification. Understanding of the most energetic events in the universe requires deep knowledge of plasma physics. Such research is essential to interpreting electromagnetic signatures from events like black hole mergers in this era of multi-messenger astronomy. Plasmas enable technologies essential to our everyday lives, including plasma-processing of semiconductor devices, which is key to the trillion-dollar information technology industry. There is potential to expand these applications with significant societal benefit; for example plasma-enhanced chemistry could help address energy security and climate change by providing ways to make products from carbon-free electricity, as well as purifying water and providing new medical treatments.

This report details opportunities to accelerate the development of practical fusion energy and to advance the frontiers of plasma science and engineering. Importantly, it outlines a strategy to act on these opportunities for DOE Fusion Energy Sciences (FES).

Embracing opportunities to form partnerships that accelerate progress in research and development is an important theme of this report. Partnership opportunities exist within the federal government, internationally, and with industry. DOE FES is the primary federal sponsor for fusion research, but other agencies have made important investments including DOE ARPA-E, DOE Advanced Scientific Computing Research (ASCR), and the Department of Energy National Nuclear Security Administration (DOE NNSA). Owing to the interdisciplinary nature of the field and to the multitude of applications there are many federal agencies that invest in broader plasma science and engineering, including the National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), Department of Energy High Energy Physics Program (DOE HEP), Office of Naval Research (ONR), and the Air Force Office of Science Research (AFOSR). Better coordination is warranted and could result in more efficient use of federal resources and enable more rapid progress in advancing plasma science and engineering and developing fusion energy.

Fusion energy and plasma science research are both global endeavors. Many nations recognize the promise of fusion energy and have made significant investments in research and development. International collaboration has been critically important to progress. This has been particularly true in the quest to address a top priority for the global fusion research community: experimental access to a burning plasma, where energy released by fusion reactions is the dominant heating mechanism within the plasma. The international community, with the US as a key partner, is collaborating to construct the ITER experiment in France to achieve this goal. At the time of this writing, the ITER construction project is more than 70% complete toward first plasma. The NASEM Burning Plasma Report highlighted the importance of the ITER project to the US fusion program, stating that it provides the most compelling path to accessing a burning plasma at reactor scale. However, significant research and development is required in addition to ITER to produce electricity from fusion. Additional investment supporting that R&D is needed in parallel with ITER to advance the science and technology of a fusion pilot plant in a timely manner. While other international parties are considering a reactor scaled directly from ITER, the NASEM Burning Plasma Report recognized that this approach is too large and expensive to be economically competitive in the US market when compared to other carbon-neutral energy technologies. Consequently, the NASEM Burning Plasma Report instead set forth a unique US vision for fusion energy using scientific and technology innovations to target the development of a low capital cost fusion pilot plant. This emphasis on developing innovative, world-leading solutions makes the near-term investments in R&D even more critical as other nations continue to invest in new fusion facilities that advance their own approaches to fusion energy development.

Likewise, research in fundamental plasma science is vibrant and growing internationally, with activity spanning scales ranging from the sub-atomic to the cosmic, from low temperature atmospheric plasmas to the most extreme conditions in the universe. Shrewd investments by DOE over the past few decades in world-class facilities have enabled the US to be at the forefront of pioneering plasma research. However, such scientific leadership requires agility and continuous nurturing. In some instances, the US is losing its leadership position. For example, the recent NASEM report *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, highlights how the US has already lost leadership in the high-intensity lasers that are essential for high energy density science. Although the chirped-pulse laser amplification technology that led to petawatt lasers was developed in the US, the vast majority of high-intensity laser systems are now being built in Europe and Asia. This long-range plan describes a path to regain a leadership position in fundamental plasma science and its applications in the US.

Fusion energy and plasma science research advances fundamental science, but also translates to direct commercial application. The ultimate goal of fusion energy research is the development of commercial fusion power. The fusion energy industry is already taking root but realizing the ultimate goal of producing power will require additional support to help it become firmly established. The last decade has seen about $2B invested worldwide in fusion energy development in the private sector. Internationally, the United Kingdom and China have already established multi-hundred million dollar partnership programs to attract private fusion energy companies. Therefore, it is imperative that the US strengthens partnerships in the private sector to accelerate the development of fusion power in the US and maintain a leadership position in the emerging fusion energy industry. For decades, plasma technologies have played a ubiquitous role in manufacturing, crucial for the fabrication of microelectronic circuits, lighting, optics, advanced materials, materials processing, and much more. The future looks even more promising. Recent research suggests that plasmas will influence much of the future economy, playing a decisive role in technologies that convert electricity from carbon-free sources to the products that drive society, as well as in future medical treatments, aerospace, particle accelerators, advanced X-ray sources, and agriculture. Countries that establish a means to solve the science questions that make these technologies possible and facilitate technology transfer from academic research to commercial applications will position themselves to lead tomorrow's economy. This long-range plan outlines ways in which the US can position itself to lead in both commercial fusion energy and other plasma-based technologies.

This report marks the first time a strategic planning process for DOE Fusion Energy Sciences has been undertaken that addresses both fusion energy and plasma science and that has had a significant, community-led portion of the process. The strategic planning process involved two stages: a community-driven stage followed by a stage led by the Fusion Energy Sciences Advisory Committee, using input from the community process. The community-driven phase, the year-long Community Planning Process (CPP), was organized by the APS Division of Plasma Physics. The process was invaluable and resulted in a consensus document, the CPP report, that not only enumerates scientific and technological opportunities, but also provides guidance for prioritization. The CPP report formed the basis for this strategic plan and remains an essential companion to this report for those looking for more technical detail on specific initiatives.

Technology and Science Drivers

As acknowledged by the NASEM Burning Plasma Report, the NASEM Plasma Decadal, and Community Planning Process reports, Fusion Science and Technology has reached a level of maturity that calls for Fusion Energy Sciences to broaden its focus from the plasma core of a fusion reactor towards a holistic energy mission. At the same time, these reports also show that Plasma Science and Technology outside the fusion mission deepens our understanding of the universe and lays the foundation for creating transformative technologies ranging from microelectronics to medicine to new materials and particle accelerators.

The energy mission is driven by the urgent desire to address climate change and energy security on a relevant time scale, which requires focus on activities that resolve the critical challenges of fusion energy in the next two decades. This mission-driven program is founded on the steady progress in plasma science, ITER construction, computational and predictive modeling capabilities, and a burgeoning investment in private fusion enterprises. However, the least developed domain in the mission portfolio is within Fusion Materials and Technology (FM&T). Fulfilling the energy mission demands a shift in the balance of research towards FM&T, which connects the technology and science drivers of Sustain a Burning Plasma, Engineer for Extreme Conditions, and Harness Fusion Energy. The program's renewed attention to economic viability distinguishes it from those of other ITER partners. It leverages US innovation, leadership, and technology advances to address the key gaps in fusion plasma science, nuclear science, materials science, and enabling technology that will be required to construct a fusion pilot plant (FPP), anticipated to be the key remaining step to enable commercial fusion energy. Critical gaps in FM&T will have to be closed for any choice of plasma core in an FPP, and they have the potential to become pace-limiting without immediate investment. Such a program will create US leadership in a broad range of disciplines through innovation and rigorous scientific inquiry.

A critical need in the quest for fusion energy production is the ability to sustain a burning plasma by controlling and predicting burning plasma dynamics. Burning plasmas, in which the heating is primarily due to the energy released from fusion reactions, pose challenges to stability and control that are not fully accessible by present experiments and for which significant uncertainty exists. Addressing this requires establishing scenarios for maintaining high performance in a burning regime and preventing damage associated with transient events, through the development of tools to predict, avoid, and mitigate such events. The tokamak approach for the plasma core is the most technically advanced and mature confinement concept. A tokamak FPP will require finishing critical research on existing domestic facilities, and significant participation in the ITER research program that will enable the acquisition of knowledge in burning plasma physics as well as in materials science and technology. New collaborations with industry potentially offer pathways to accelerate access to burning plasma conditions. Complementing these two top priority areas is research into non-tokamak confinement approaches, including stellarators, inertial fusion energy, and other alternate confinement approaches. Investment in this area is important as both a risk-mitigation strategy for the tokamak approach, and to support innovations that have the potential to accelerate progress towards an FPP and deployment of commercial fusion energy.

A fusion pilot plant will produce heat, particle, and neutron fluxes that significantly exceed those in present confinement facilities, and new innovative approaches and materials will need to be developed and engineered for the extreme reactor conditions anticipated. These intense conditions affect all regions of the device in distinct ways, including the plasma-facing components (PFCs), structural materials, functional materials, magnet materials, diagnostic materials, and ex-vessel components. In a fusion pilot plant, high fluxes of 14 MeV neutrons produce damaging effects in materials, which are presently poorly understood. A scientific understanding of how the properties of materials evolve and degrade due to fusion neutron exposure is needed to be able to safely predict the behavior of materials in fusion reactors. Even those components not directly exposed to high fluxes from the plasma still experience a complex multi-factor environment including high temperatures, tritium migration and trapping, material interfaces, and high stresses. Innovative approaches and new developments will access integrated solutions to these harsh conditions.

Interlinked with a burning plasma and materials are the key systems required to harness fusion power, breed fuel, and ensure the safe operation of the reactor. Before a fusion pilot plant is constructed, materials and components must be qualified, and a system design must ensure the compatibility of all components. Just as the plasma and materials in a fusion reactor will need to advance beyond today's capabilities, the balance of plant equipment, remote handling, tritium breeding, and safety systems will also require significant advances.

Pursuit of the research encompassed by these three technology and science drivers is essential to retiring the risks to an acceptable level for a fusion pilot plant, and will enable the US to pursue a swift, innovative and economically attractive path to realizing fusion energy production. The societal benefit of establishing a new carbon-neutral power source, and growing the industry that supports it cannot be understated and is one of the most transformational technologies in the field of plasma science. On the road to achieving this scientific grand challenge are myriad additional spinoff technologies and fundamental investigations that can reveal new knowledge about the universe.

The field of plasma science and technology is a rich and diverse landscape, from the search for accurate theoretical descriptions of the complex emergent behavior of the plasma state, to the production of matter at extreme conditions exceeding even those at the core of giant planets or stars, to low temperature plasma science that can translate into new technologies. Expanding the fundamental understanding of plasmas and its interactions with its surroundings across wide ranges of temperature and density underpins not only fusion physics but the practical application of plasmas for manufacturing, medicine, and agriculture. The Plasma Science and Technology component of the FES mission is impelled by three main scientific and technological drivers: strengthen the foundations, understand the plasma universe, and create transformative technologies. Together, these drivers tackle the plasma questions of highest scientific impact and urgency, and foster innovation by spurring exploration as dynamic as the processes in plasmas themselves. The programs, initiatives, and facilities identified here represent an opportunity to grow and fortify US leadership by strengthening investment in research areas of high potential, while leaning forward with new capabilities and facilities, and tapping the collective wisdom of the scientific community through a series of networks, collaborations, and partnership opportunities.

Strengthening the foundations of plasma science deepens our fundamental understanding of nature. It is an exciting time in this fast-paced area as new experimental capabilities unlock unprecedented plasma regimes, while new theories and computational methods provide outstanding insight to decipher them. Extremely intense lasers are making compact particle accelerators possible, and may soon reach nonlinear quantum electrodynamic (QED) regimes where pair plasmas will be created directly from light. Pulsed power facilities compress matter to such high density that the behavior of the warm dense plasma it produces is fundamentally differently from known states of condensed matter or plasmas. Due to the high electrical conductivity, magnetic fields can be compressed with the plasma, approaching strengths only found in astrophysical objects such as white dwarfs. Coupling these drivers with X-ray free electron lasers allows exquisite measurements of these novel states of plasma. At the same time, tabletop-scale experiments create and trap exotic states of antimatter and strongly correlated plasmas, which can be so sensitively diagnosed that they can be used to test fundamental symmetries of nature. Strengthening the foundations. of plasma science will continue to require research and facilities at a range of scales.

Understanding the plasma universe is essential to learning about our origins and the evolution of our universe. Nearly every aspect of the cosmos is influenced by plasma, from lightning and aurora in the Earth's atmosphere, to stellar winds that fill the space between planets and stars, to accretion disks surrounding supermassive black holes at the centers of the galaxies, to the particle jets launched from the most distant and ancient quasars. Viewing astrophysics through the lens of plasma physics is crucial given recent advances in multi-messenger astronomy and spacecraft missions. As spacecraft such as the Parker Solar Probe and Solar Orbiter "touch the sun," knowledge of plasma mechanisms will play a key role in interpreting this frontier of space exploration. In addition to theoretical and computational study, exploration of the plasma universe can be conducted through experiments on Earth. The breadth of conditions observed in the plasma universe requires a wide-ranging laboratory approach from high energy density laser experiments to magnetized plasma facilities at multiple scales.

Plasma science and technology lays the foundation for creating transformative technologies unique in implementation and application. The realization of a fusion power plant opens the door to ubiquitous carbon-free electricity. Plasma-based technologies promise unique pathways to convert that electricity to the products that power society, potentially revolutionizing the way chemicals are manufactured. Already, they promise the realization of novel materials that are not possible to manufacture by conventional means, such as functionalized nanoparticles for drug delivery and new materials relevant to quantum information systems. The next generation of rockets, powered by fusion, may enable human exploration of the solar system and beyond with fast transit times. The next generation of ultra-fast, compact electronic devices such as cell phones and computers will rely on plasma science to fuel advancements in semiconductor manufacturing. Novel, precision treatment therapies for cancer and for antibiotic resistant bacterial infections are now within reach, buoyed by advancements in the areas of atmospheric pressure plasmas and advanced plasma-based ultra compact accelerators.

Programs and Facilities to execute the strategic plan

Aligning the program with the six technology and science drivers will require redirection of programs and development of new facilities. Collaborations with international and privately funded research programs are important components of this strategy, and participation in ITER is considered essential for obtaining access to a high-gain burning fusion plasma. Rigorous and impactful scientific inquiry is cultivated by leveraging areas of current US leadership, partnerships, and priority research areas organized to highlight both the discovery nature of general plasma science and high energy density physics, while emphasizing the potential of plasma-based technology for translational research. Success in all of these areas will require robust support for foundational cross-cutting research in theory, modeling, and computation, diagnostic development, and transformative enabling technologies, as well as building a more diverse and inclusive workforce.

Research Program Areas

A number of new or expanded research program areas are urgently needed to fulfill the mission of developing our fundamental understanding of plasmas and to progress towards a fusion energy source with FPP readiness by the 2040s. These research program elements are described here at a high level, targeting the specific technology and science drivers identified above, and are not in priority order (prioritization is provided within the budget scenarios in Chapter 2).

FPP System Design and Integration: A central overarching priority is to form a domestic multi-institutional, collaborative FPP design and study program. This effort will provide the resources and coordination to integrate critical research advances made across the FES portfolio into attractive FPP concepts. It will need to merge advances in our understanding of burning plasma physics, with the capabilities of new fusion materials and technologies, as well as attention to safety-related issues (e.g. tritium and activation product transport, and stored energy sources including the plasma, magnets, and cryogens) and licensing. Balance of plant considerations demand the development of supporting technologies for remote handling and supporting measurements for Reliability, Availability, Maintainability, and Inspectability (RAMI) of the plant. Participation by private as well as public stakeholders is essential to ensure economic attractiveness and innovations made outside the public program are appropriately considered in developing these concepts. An essential component underpinning this effort is a strong theory and computation program, including the advancement of multi-scale, multi-physics theory and modeling capabilities necessary to predict the complex interactions between numerous plasma, material, and engineering processes that will occur within a fusion pilot plant (FPP). Moreover, accelerated progress and increase in readiness of multiple systems are needed to safely design and operate a fusion reactor, including advances in diagnostics, instrumentation, data handling and automated real-time decision making. This design effort should also give significant attention to activities agnostic to the plasma core and specific areas in which solutions based on the tokamak as baseline approach are contrasted with concept studies of possible advantages from different plasma core concepts like stellarators, alternates or IFE. As part of the national design effort, targeted studies for new concept exploration or performance extension devices should be pursued to provide an information basis for the design, decision and pursuance of such new facilities.

Fusion Materials & Technology: Critical developments are needed in fusion materials, magnets, and heating and current drive actuators that comprise this area. Technology advances are needed to handle the extreme conditions expected in future fusion reactors, and to harness fusion energy and breed fuel. In addition to advancing key research on existing facilities (such as linear plasma devices and in-pile fission irradiation), resource enhancement is needed to a level that allows timely resolution of critical FPP design questions. Because of the significant time scales involved in facility development and subsequent research, immediate action is needed. Increased investment in theory and simulation supporting the research on these facilities is also needed. Focus is given to the development of Plasma Facing Materials and Components, Structural and Functional Materials, and Fusion Blanket and Fuel Cycle elements needed for an FPP. Diagnostic advancements for fusion materials studies are needed to understand the interaction of materials with the fusion environment. Magnets are an integral feature of magnetic fusion configurations, and it is highly desirable to develop magnets with higher fields, higher operating temperatures, higher reliability, streamlined manufacturing processes and reduced production costs, all of which improve the performance and/or lower the costs of an FPP. Industry has made significant progress in developing the relevant magnet technology, including high-temperature superconducting magnets, and the federal program should complement and, when possible, collaborate with these activities. Launching structures for radio frequency plasma heating and current drive actuators must be made of new materials to withstand the neutron and plasma environment, have integrated steady state cooling, and more acceptable long-pulse reliability. Efficiency improvements including the source, the transmission, and the plasma coupling must be developed to enhance fusion power plant attractiveness. The lack of appropriate materials, technology and knowledge necessary to complete FPP designs with respect to material performance under nuclear conditions and complex integrated fusion core components is an international gap. The US is poised for leadership in this area by targeted investments into unique facilities.

Fusion Plasma Core: The tokamak is the most technically advanced approach for use as a fusion reactor power core. ITER is the largest single investment by DOE-FES, and a US ITER research team needs to be formed to leverage this investment. The US ITER research team will make essential contributions to achieving the high gain mission for ITER, exploit unique access to a burning plasma at the reactor scale, and enable gap closure of nuclear science and engineering toward an FPP. The existing DIII-D and NSTX-U national tokamak facilities are key to preparation for the study of burning plasmas in ITER, as well as in other planned and future private devices. Additional research on these facilities, in combination with private and international collaboration, continuing support for existing university tokamak programs, and utilization of US expertise in theory and simulation, is needed to advance solutions to remaining technical gaps. These gaps include disruption prediction, avoidance, and mitigation; plasma facing component integration, and FPP-relevant scenario development. Advances in our understanding of plasma physics and enabling technologies have opened paths to lower capital cost tokamak FPPs, but also bring additional scientific and technical challenges to overcome. These challenges motivate the construction of a new world-leading domestic tokamak, which would be uniquely situated to develop integrated solutions in a timely fashion. In order to mitigate risks associated with the tokamak approach, alternative pathways to fusion are also pursued, with the potential to lead to more economic fusion power in the longer term by capitalizing on US expertise. Quasi-symmetric stellarators are considered as well as alternate plasma core solutions beyond the tokamak and stellarator. These alternate pathways are supported at three different levels, from basic validation of the physics, through development of self-consistent solutions, to demonstration of integrated solutions. An IFE program is re-established, taking advantage of US leadership in high energy density physics and progress that the NNSA has made in inertial confinement fusion toward high yield.

General Plasma Science (GPS) Program: GPS research explores the fundamental behaviors of plasmas. This includes foundational theoretical descriptions of plasma dynamics, numerical methods to model multi-scale behavior, and experiments that test if our understanding is true. Such foundational research serves as the basis for all areas of plasma science and technology, ranging from the laboratory to astrophysics. Although motivated primarily by the desire to understand nature, many of the physics processes studied have direct relevance to fusion and other technological applications. The GPS program funds research at a range of scales, including operations and construction of the Basic Plasma Science Facility at UCLA, the Wisconsin Plasma Physics Laboratory, the Magnetized Dusty Plasma Experiment at Auburn and the Facility for Laboratory Reconnection Experiments at Princeton Plasma Physics Laboratory. A major component of the GPS research program is the long-standing, successful NSF-DOE Partnership in Plasma Science and Engineering.

High Energy Density Laboratory Plasma (HEDLP) Program: HEDLP research explores and applies novel regimes resulting from the extraordinary ability to concentrate power—in many cases more power than the world's total electric generating capacity in an area smaller than the end of a human hair for a brief fraction of a second. This creates new states of matter ranging from condensed matter to warm and hot dense matter and plasmas relevant to astrophysical phenomena, stellar properties/processes and fusion reactors. Self-organized, far-from-equilibrium plasmas are probed and controlled, enabling unique applications such as new accelerators and materials. This program has a very successful history of partnering with DOE-NNSA, NSF, and DOE-HEP to fund research on a number of mid-scale laser, pulsed-power, and XFEL facilities.

Plasma-Based Technology Program: Plasma technologies currently researched within the PST portfolio include low temperature plasmas and plasma-based accelerators. These technologies offer benefits directly to the public by enabling modern conveniences such as cell phones, computers, advanced drinking water purification, and security and medical methods. They furthermore underlie key industries such as semiconductor manufacturing and materials processing thus directly fueling the economy through innovation as well as maintaining core competence and leadership in these critical areas. To highlight the growing importance and promise of this area, a plasma-based technology program that consolidates critical efforts will focus these efforts and facilitate efforts for technology transfer.

Networks: Collaborative networks of researchers and facilities can provide enormous value as a coordinating organization and mechanism for leveraging resources and capabilities. LaserNetUS is a successful model that brings together 10 unique mid-scale laser facilities and opens up opportunities to a large number of new users. In a similar vein, the establishment of a MagNet, centered around basic magnetized plasma and laboratory space/astrophysics; a ZNet for pulsed-power science and technology; and an LTP-Net for low temperature plasmas could similarly support growth and enable collaborative research in their respective areas. These networks can furthermore encourage cross-fertilization as researchers work on multiple facilities, and will facilitate the training of students. Coordination and access to computational/theoretical models, diagnostics, and other resources in support of experiments can also be established. These network structures also position the US to be more competitive, as investments, technology development, and future planning can be implemented more strategically by engaging the full community.

Facilities

A number of new mid- to large scale facilities are urgently needed to meet the goal of FPP readiness by the early 2040s, and to realize the goals of plasma science and technology. The elements of the following list are roughly grouped by topical area and are not in priority order.

Fusion Prototypical Neutron Source (FPNS): The science of material exposure to fusion neutron fluxes is a central gap of the international fusion program. No facility exists in the world that can generate the necessary fluence, energy spectrum, and helium production level in the lattice of candidate materials. FPNS concepts that utilize either existing facilities like accelerators or commercial units combined into a cost effective system can be a fast track forward. FPNS provides leadership opportunities based on existing expertise in nuclear materials in the US program, by enabling the fundamental explorations of fusion nuclear material science that needs to be combined with a reinvigorated neutron theory and computation program. Moreover, accelerated access to fusion neutron exposure is an area of extreme interest to the fusion industry with significant opportunities for near-term public-private partnership.

Material Plasma Exposure eXperiment (MPEX): MPEX is under construction and will provide a unique capability to study plasma-material interactions under conditions that are prototypical for a reactor divertor regime as far as the near wall plasma material interface is concerned. The capability to expose irradiated materials to these plasma conditions and conduct rapid turn-around in-situ and ex-situ material characterization are the most important project elements that need to be met as key program deliverables towards an FPP.

High-Heat-Flux (HHF) testing facilities: Testing capabilities to explore properties of materials and plasma-facing components, both solid and liquid, under high heat fluxes address a key gap towards FPP material definitions. Experimental capabilities to conduct fundamental testing on coupon levels (cm scale) are a necessary testbed for model validation of material properties. The coupon-level testing is a prerequisite for component-level testing (tens of cm to m scale) to qualify components for a fusion pilot plant. Accordingly, testing-facilities for both levels of high heat flux materials research are required.

EXhaust and Confinement Integration Tokamak Experiment (EXCITE): High magnetic field approaches to a tokamak-based FPP bring forward specific scientific and engineering challenges. High divertor power exhaust solutions need to be integrated with sustainment of high power density plasma cores, which are needed for generation of significant fusion power. Both the NASEM burning plasma report and the CPP report identify the need to solve these challenges in an integrated fashion, rather than at separate facilities. This requirement motivates construction of a new domestic tokamak, previously referred to as NTUF ("New Tokamak User Facility") within the CPP report.

Blanket Component Test Facility (BCTF): The research and development program on blanket materials and transport phenomena will culminate in the design and fabrication of blanket section prototypes, which are to be tested in a Blanket Component Test Facility (BCTF). Such large component-scale testing in an environment that is as prototypic as possible but without neutrons or radioactive materials, is an essential accelerating element in the FM&T domain.

Mid-scale Stellarator: A proof of concept experiment is needed to demonstrate improved steady-state plasma confinement in combination with a novel non-resonant divertor. Development of this research line provides risk mitigation for the mainline tokamak approach and bears the potential of a commercially more attractive fusion system. This stellarator facility would therefore be a discovery oriented facility that has a large innovation potential.

Volumetric Neutron Source (VNS): The VNS is proposed as an evolution of the fusion neutron science focus established with FPNS to test integrated material and structure elements on a component level. A concept assessment study for VNS should examine the plasma physics development required for the concept, the device requirements for the desired neutron fluxes (major scale-up of the plasma performance and engineering systems), and the relevance of the configuration to a tokamak or other FPP components to determine if such a facility should be pursued. Facility concepts should be pursued with all due speed if assessment results warrant it.

MEC-Upgrade: An upgrade to the Matter in Extreme Conditions (MEC) endstation at the Linac Coherent Light Source (LCLS) would enable the co-location of a PW-laser operating at 1–10 Hz repetition rate and a multi-kJ long pulse laser with our only domestic X-ray free electron laser to tackle physical and chemical changes at fundamental timescales, and explore new regimes of dense material physics, astrophysics, planetary physics, and short-pulse laser-plasma interactions. The MEC-U proposal has achieved CD-0 and is currently in preparation for CD-1.

Solar Wind Facility: How the solar wind is accelerated, heated, and driven turbulent is among the most persistent and important open questions in plasma science. It is an opportune moment to develop, in concert with advanced space missions, a next-generation experimental facility to isolate, control, and diagnose plasma phenomena responsible for the complex solar wind behavior, at relevant scales. This facility would leverage and coordinate existing laboratory space/astrophysics research groups as experimental conditions needed to pursue solar wind related questions can also benefit research in broader astrophysical contexts. Such a venture would be a prime opportunity to coordinate amongst interested funding agencies including primarily NSF and NASA, as well as ONR and AFOSR.

Multi Petawatt Laser Facility: Multi-10s of petawatt laser systems can produce light pressures in the exa-Pascal regime, copious amounts of radiation, and extremely bright beams of energetic particles, including electrons, ions, neutrons, or antimatter. The novel capabilities enabled by multi-PW lasers open new frontiers in research and development such as particle acceleration and advanced light sources, high-field physics and nonlinear quantum electrodynamics (QED), and laser-driven nuclear physics. As identified in the BLI Report, there is a need for the US to develop ultrahigh-intensity technology and build an open-access laser user facility with multiple beamlines at 10–100 PW peak powers.

High Repetition Rate Laser Facility: New high-repetition-rate (10 Hz to kHz) laser systems coming online represent a fundamentally new system architecture for HED. The >1000x increase in shot rate over today's systems, coupled to emerging technologies such as machine learning and additive manufacturing will result in an enormous acceleration in the rate of knowledge acquisition. Such high-rep-rate high energy lasers further open the door to unprecedented temporal and spatial resolution of HEDP phenomena including GeV-class electron beams and precision HED pumps and probes. Recent community reports (NASEM, BLI) have clearly outlined the urgent science case and FES mission-relevant needs demanding a short-pulse, high-peak power, high-average power laser system. This may be an area for partnering with DOE HEP which may take the lead on this facility.

Mid-scale Z pinch: Extremely strong magnetic fields over macroscopic volumes are only accessible via pulsed-power facilities, opening up the physics of plasmas in a way that other plasma drivers cannot. Current US facilities are either very large and complex (the 26-MA Sandia Z-Machine with <1 shot/day) or too small (~1 MA or less) to address the breadth of science expressed by the community. There is clear community interest in establishing a pulsed-power facility at an 'intermediate' size (up to 10 MA) accessible to the academic community, with a higher shot rate than Z, yet still capable of fielding fusion-relevant and HED experiments. Further, such a facility could explore driver technologies and pulsed-power science for next-generation larger-scale pulsed-power devices such as a 60 MA "Z-Next". This facility would be a good opportunity for FES to partner with another agency such as NNSA or NSF which might take the lead.

Process and Prioritization Criteria

The following criteria express the principles used to prioritize projects and programs discussed in this report. Consensus criteria and guidance for prioritization within program areas were developed by the research community during the CPP process. This guidance is incorporated in the criteria below, which were used for whole portfolio prioritization. In applying the criteria and following the charge language, we assume that the ITER construction project will be successful and we thus focus on the non-ITER-project portion of the budget.

Alignment: Align projects and programs with the technology and science drivers, to achieve the fusion mission, specifically the path to an FPP, and to advance fundamental plasma science and enable societally beneficial plasma applications. Balance technological development with scientific discovery, recognizing the importance of both as the sources of innovations that will benefit the entire program.

Urgency: Prioritize the most expeditious path to fusion energy and other plasma technologies that provide compelling solutions to urgent issues, including sustainable, carbon-free power production, advanced medical therapies, and more efficient industrial processes.

Innovation: Embrace innovative research, new developments in technology, and interdisciplinary connections to address key challenges. Reduce the time and cost to develop usable fusion energy and other plasma applications.

Impact: Implement a logical sequence of programs that increases scientific and technological progress relative to investment, reduces the risks associated with the FPP mission and the technology and science objectives, and takes into account time constraints and impacts on the overall program.

Leadership: Establish and maintain US leadership, including world-leading facilities, science, and industries that attract international participation. Recognize federal, industry, and international efforts in fusion and plasma development and form partnerships whenever possible.

Stewardship: As experimental capabilities are developed and program transitions occur, ensure the continued productivity of the essential workforce to maintain scientific and technological progress. Engage all stakeholders in executing the program, including national laboratories, industry, and universities.

Chapter 2
Recommendations and Budget Scenarios

The fields of fusion energy research and plasma science and engineering were described in Chapter 1, along with the scientific and technological opportunities they present. In this Chapter, we present recommendations on how the DOE Fusion Energy Sciences research program should capitalize on those opportunities to move aggressively toward practical fusion energy, deepen our understanding of plasma science, and create transformative plasma technologies. The recommendations are worked through three different budget exercises, detailing how the recommendations might be implemented under specific funding scenarios. The recommendations are grouped into two categories and three sub-categories. Overarching recommendations are independent of specific programs or facilities but viewed as essential to successful execution of the FES research program. Project and Program Specific Recommendations are grouped into three subcategories: Fusion Science and Technology Program recommendations, Plasma Science and Technology Program recommendations, and Cross-cutting recommendations that apply to all programs. The order of presentation of these recommendations does not imply priority; all recommendations should be acted on in order to fully realize the strategic plan. Prioritization of activities is expressed through the budget scenario descriptions below.

Overarching Recommendations

The Community Planning Process (CPP), completed early in 2020, resulted in the fusion and plasma science research community coming to consensus on new directions for FES-funded research. This first recommendation aligns the strategic plan with the consensus view, as summarized in Chapter 1:

– Recommendation: Align the program with the six technology and science drivers in order to establish the scientific and technical basis for a fusion pilot plant by the 2040s and advance fundamental understanding of plasmas that translates into applications that benefit society.

Experimental research and technology development in fusion energy and plasma science requires state-of-the-art facilities, often at large scale. US participation in the international ITER experiment is critical to accessing burning plasmas at reactor scale. The US has invested significantly over the last decade in the design and construction of ITER and will continue to do so over the coming decade to ensure this access. However, there are additional high-priority research gaps that require the development of large-scale facilities to be successfully addressed. Outside of the important investment in ITER, there has been little investment over the last decade in the development of major new experimental capabilities. Addressing the technology and science drivers will require continuing investment in the design, construction and operation of facilities that provide important new capabilities. Such investment is necessary to maintain a vigorous scientific program and to achieve necessary breakthroughs in a number of areas. This strategic plan provides a framework for sequencing the development of these new capabilities.

– Recommendation: Resources for ongoing design and construction of major new experimental facilities should be established in the DOE Fusion Energy Sciences budget.

Although large scale facilities are essential to make progress in many areas, important aspects of the technology and science drivers can be successfully addressed through the development of small and medium scale experimental facilities. Such facilities are amenable to siting at universities, where investments can have high impact, provide leadership opportunities to faculty and junior scientists, and help develop the workforce needed to execute this strategic plan.

– Recommendation: Opportunities should be provided for developing new experimental capabilities at a range of scales, as appropriate to address the goals of this strategic plan.

The strategic plan should be regularly updated to adapt to new scientific discoveries, technological breakthroughs and other changes in the research and development landscape.

– Recommendation: This long-range planning process, including a strong community-led component, should be repeated every five years in order to update the strategic plan.

Strategic planning is most effective if ideas for major new experimental capabilities are developed to the pre-conceptual stage, preferably with mission need and scope well defined and a preliminary cost range established. The Critical Decision process within DOE provides a framework for accomplishing this goal and utilizing this process to routinely refine the design of needed new experimental facilities is highly desirable.

– Recommendation: Maturation of pre-conceptual designs, scope, and costing for proposed new experimental facilities should be part of regular program activities.

Fusion and plasma science research has strong and growing commercial connections to US industry. These connections exist across the whole portfolio of industry applications and an opportunity exists for DOE to take a more active role in translating advances stemming from federally funded research into commercial applications. Public-private partnerships (PPP) should be formed with private industry and used as a paradigm for accelerating fusion and plasma science research that would present opportunities for beneficial partnerships between the government-funded program and private companies. Research conducted in the private sector can benefit from federally supported programs by offering more cost-effective pathways to retire risk in key gap areas while establishing the industrial infrastructure critical for the next steps in fusion energy and plasma technology. Access to public facilities and programs can be leveraged to solve technical problems by private companies that do not have the public sector's capabilities. Public-private partnership should be used as a tool to engage and stimulate industry involvement. DOE Fusion Energy Sciences has already established successful PPP programs, notably the Innovation Network for Fusion Energy (INFUSE). These activities should be expanded and new public-private partnership programs, including milestone-based cost-share programs, should be developed. Investment in PPP activities should align with priorities in the strategic plan and be balanced by robust investment in federally-funded programs to maximize effectiveness of the partnership. Further discussion of specific opportunities in PPP is offered in Appendix A.

– Recommendation: Expand existing and establish new public-private partnership programs to leverage capabilities, reduce cost, and accelerate the commercialization of fusion power and plasma technologies.

Research and development in fusion energy and plasma science and technology is inherently interdisciplinary. Given the broad range of applications where these fields have relevance, there is also a range of federal agencies that currently provide research support including the National Science Foundation (NSF), DOE Advanced Scientific Computing Research, DOE High Energy Physics, DOE National Nuclear Security Administration, DOE ARPA-E, NASA, Air Force Office of Sponsored Research, and the Office of Naval Research. Coordination among these federal programs has led to extremely successful research programs; the NSF-DOE Partnership in Basic Plasma Science and Engineering is a prominent example. Expanding on these successes and increasing program coordination could make better use of federal resources and enable more rapid progress toward development of fusion energy and toward advancing plasma science and engineering.

– Recommendation: Explore and implement mechanisms for formal coordination between funding agencies that support fusion and plasma science research.

Successfully addressing the challenges of bringing fusion power to the grid and advancing the frontier of plasma science requires innovation, creativity and a talented, multidisciplinary and diverse workforce. There are barriers to achieving this workforce that should be addressed in order to achieve the goals in this strategic plan. First, the fusion and plasma community is not accessing the available talent pool in our current workforce. Data show that our research community has significant deficiencies in workforce diversity, with participation from women and underrepresented minorities below national averages for other subfields of physics and engineering. This is not just an issue of recruiting talent, but also of retaining talent, something that is affected by the culture within the community and that could be addressed through embracing equity and inclusion.

Second, DOE lacks the tools necessary to direct development of the needed workforce to execute this strategic plan. The Office of Management and Budget recently implemented a policy change that significantly limits workforce and outreach programs at DOE. This policy was intended to reduce duplication of education and outreach activities at federal agencies, but had the unintended consequence of eliminating discipline-specific outreach and workforce programs that were not being duplicated at other agencies.

Below we offer overarching recommendations on diversity, equity and inclusion and workforce development. We dedicate Appendix B to more specific recommendations.

- Recommendation: DOE and FES should seek to implement policy changes that improve diversity, equity and inclusion within the FES research community.
- Recommendation: Restore DOE's ability to execute discipline-specific workforce development programs that can help recruit diverse new talent to FES-supported fields of research.

Program and Project Specific Recommendations

The following recommendations address specific elements of the Fusion Science and Technology (FST) and Plasma Science and Technology (PST) program components. As with the earlier recommendations, resource priorities across and within program components are delineated in the budget scenarios in the following section, and not by recommendation ordering.

Fusion Science and Technology Recommendations

The recommendations described below are targeted toward realizing the overall mission of establishing the technical basis for an FPP in the 2040s. As such, it is implicit that all recommendations are implemented in time to be consistent with achieving this goal.

The underlying theme guiding the overall strategic plan is the need to move urgently and aggressively toward the deployment of fusion energy. The design, construction and operation of a fusion pilot plant (FPP) is recognized as a critical milestone toward that goal. Here a coordinated program is delineated that develops FPP concepts that can advance to engineering designs, and that can rapidly adapt to advances in understanding and new innovations. Effort is also needed to bring physics modeling efforts together with engineering tools in order to consider issues beyond the fusion core, including balance of plant equipment, licensing, remote handling, maintenance, and reliability. Cutting edge physics, materials and engineering, and integrated models need to be applied to viable confinement concepts and operating scenarios, so as to continuously inform research needs and priorities. A diverse range of stakeholders exists for an FPP in both the public and private sectors, and they will all need to participate in such a coordinated effort.

– Recommendation: Initiate a design effort that engages all stakeholders and establishes the technical basis for closing critical gaps for a fusion pilot plant.

Construction of a viable fusion pilot plant will require significant technology development beyond the burning plasma itself. Critical enabling technologies such as plasma facing components, structural and functional materials, and breeding blanket and tritium handling systems are currently not advanced enough for an FPP. The time required to develop these technologies at present levels of support is incompatible with the goal of a fusion pilot plant by the 2040s. Increased support for these program areas is therefore critical. Essential to this effort is an increased emphasis on foundational fusion materials and technology research. This includes the expansion of theory and modeling efforts that support advancing technology readiness levels (TRLs), accelerating development of diagnostics and measurement systems that will function in fusion nuclear (irradiation-hardened) environments, and rapid maturation of enabling technologies.

– Recommendation: Pivot the research and development focus toward fusion materials and technology.

Fusion nuclear facilities including an FPP will require new materials to be conceived, developed and qualified for nuclear use. This process is well understood for nuclear components having a clear path that includes laboratory development, standardized testing, and regulatory oversight and approval. While mixed spectrum fission reactors are and will remain the primary workhorse for research and development and obtaining qualification-level data of irradiated materials, they do not produce the appropriate spectrum for materials irradiated in a fusion reactor core. In this region, the fusion-born neutrons will produce significant, yet largely unknown, effects on structural and non-structural components of the first wall, divertor, and blanket. In order to develop materials that withstand high levels of fusion neutron irradiation and can be qualified for FPP service, an irradiation facility that can produce the required damage and transmutation rates is necessary. The Fusion Prototypical Neutron Source (FPNS) recommended here should be of high reliability and have the flexibility to increase the damage rate. The primary utility of this facility will be to translate the measured effects of the fusion spectrum and transmutation products into codes with predictive capability. Towards this end a comprehensive program of modeling, advanced characterization, and high-temperature nuclear-structural design criteria is necessary. These tools, along with the construction of an FPNS, will build upon the US leadership in fusion materials technology.

– Recommendation: Immediately establish the mission need for an FPNS facility to support development of new materials suitable for use in the fusion nuclear environment, and pursue design and construction as soon as possible.

Physics-based understanding of plasma-material interactions (PMI), including the development of predictive capabilities for the material response and exhaust solution, is necessary to construct and qualify plasma-facing components (PFCs) for an FPP. Reaching these capabilities will require support for the completion of the scientific infrastructure, of which the Material Plasma Exposure eXperiment (MPEX) is a central piece. MPEX is a linear plasma exposure device that will be uniquely equipped to access prototypical plasma conditions in a fusion reactor divertor. The MPEX is currently in the design to build process. Additionally, high heat flux testing via a coupon-level (cm-scale samples) facility early and a component-level (tens of cm to 1 m scale) facility later, will allow for development of materials and qualification of components for an FPP. Together with the existing PMI facilities, these world-leading capabilities will allow for validation of PMI models that will form the base of PFC design tools for an FPP.

– Recommendation: Develop the scientific infrastructure necessary for the study of plasma-materials interactions needed to create plasma facing components for a fusion pilot plant by completing the MPEX and high-heat flux testing facilities.

Closure of the fusion fuel cycle via successful breeding and extraction of tritium will be critical for the sustained operation of an FPP. But breeding blanket technologies are presently at a low technology readiness level and are unlikely to advance to this demonstration stage without significantly increased research and development support. In the near term, this should entail a variety of separate-effect test stands and fission reactor irradiations to understand fundamental tritium transport properties and phenomena in solid and liquid breeder materials, and associated modeling and model validation efforts. Tritium technologies related to fueling and exhaust from the plasma, and subsequent processing, will be demonstrated at significant scale in ITER. The program should involve tritium experts in the US ITER team so as to maximally benefit from this technology demonstration. It should also support additional research and development of technologies that would minimize the size, cost, and tritium inventory of the plant required to perform these functions. Since there is no current path for the US to deploy a test blanket module in ITER or any other facility, this program should also develop a strategy for component-scale blanket testing and support pre-conceptual design and costing studies for facilities such as a blanket component test facility (BCTF).

– Recommendation: Significantly expand blanket and tritium research and development programs.

Several gaps in the tokamak physics basis need to be closed to confidently design a low capital cost tokamak FPP. These include advancing understanding of transport and stability physics for sustaining disruption-free, high-average-power output operation; energetic particle and burning plasma physics relevant to a high-fusion-gain FPP; and plasma-material interactions and material choices for exhaust solutions. Critical issues must also be addressed to integrate improved understanding into operational scenarios for an FPP. Significant parts of the tokamak physics basis can be addressed immediately through a comprehensive, multidisciplinary science program utilizing the world-leading DIII-D and NSTX-U facilities alongside important smaller-scale facilities at universities. DIII-D will focus on resolving the disruption and transients challenge, and informing long pulse steady state operation, while NSTX-U will focus on spherical tokamak plasma physics, along with PMI control and liquid metal PFC evaluations. Collaborations on planned public and private domestic and international facilities, particularly those that focus on long pulse conditions inaccessible in the US will provide unique contributions to complete the tokamak physics basis in these areas.

– Recommendation: Close fusion pilot plant design gaps by utilizing research operation of DIII-D and NSTX-U, and collaborating with other world-leading facilities.

In addition, the US should fully exploit its participation in ITER to gain experience with a burning plasma and fusion technology while benefiting from the shared cost through an international partnership. ITER is the baseline path to a reactor scale burning plasma and provides unique technology advances that will accelerate the FPP development path. To ensure timely involvement by the pre-fusion-power operation phase starting in 2028, the US urgently needs to establish a framework for developing an appropriate workforce. This should be centrally organized and activities would ramp up as the project moves toward first plasma, starting in the near term with opportunities to participate in system design and commissioning efforts.

– Recommendation: Ensure full engagement of the US fusion community in ITER by forming an ITER research team that capitalizes on our investment to access a high gain burning plasma.

Even with existing and planned facilities, it will not be possible to fully complete the tokamak physics basis needed for the US vision of a tokamak based FPP, followed by an economically attractive power plant. In particular, this vision requires demonstrating integrated strategies for handling exhaust heat fluxes well beyond what is expected to be accessible in existing or planned devices, while simultaneously supporting sustained high core plasma performance. A range of options for closing this Integrated Tokamak Exhaust and Performance (ITEP) gap were considered, including upgrades to existing facilities and collaborations on both private and international tokamaks. While these options provide excellent opportunities to partially bridge this gap, none were judged sufficient to close the fundamental core-edge integration challenge encapsulated by the ITEP gap. Closing that gap is necessary to ensure FPP readiness. Building upon the recommendations of the NASEM Burning Plasma report, we recommend the construction of a new domestic tokamak, named EXCITE (EXhaust and Confinement Integration Tokamak Experiment) in this report, as the optimal solution to closing the ITEP gap. The envisioned EXCITE design would offer a unique and world-leading combination of flexible power exhaust capabilities, plasma-facing component options, control actuators, and access to plasma conditions that would enable continued US leadership in tokamak physics into the 2030s. At the same time, it is envisioned to be a modestly sized high-field device utilizing short-pulse, non-nuclear operation to enable design and construction on an acceptable timescale at manageable cost. This approach requires an immediate, significant design and costing effort to advance solutions to the ITEP gap and confirm the EXCITE mission and scope. This activity should develop EXCITE pre-conceptual designs that allow for a more detailed assessment of EXCITE cost and technical feasibility, and benchmark them against alternate gap closure approaches such as collaborations and upgrades. This activity should include participation from private industry and international groups in order to accelerate the EXCITE schedule and reduce costs.

– Recommendation: Immediately establish the mission need for an EXCITE facility to close the integrated tokamak and exhaust gap and pursue design and construction as soon as possible.

A tokamak with solid plasma facing components is currently the mainstream path to commercial fusion. Four innovative areas aim to address key vulnerabilities of this approach, potentially leading to more attractive commercial fusion power systems while leveraging areas of US leadership.

– Stellarators offer intrinsically disruption-free operation with low recirculating power. The quasi-symmetric stellarator concept is a unique US design approach that is complemented by international collaboration at the W7-X and LHD stellarators. A new domestic mid-scale US stellarator experiment should be realized.

– Liquid metal plasma-facing components (PFC) potentially expand the reactor wall power limits and alleviate lifetime constraints due to material erosion. Low recycling, liquid lithium walls may open up pathways to high plasma confinement and compact FPP designs. Development of liquid metal PFC concepts in non-plasma test stands and existing magnetic confinement facilities should be targeted, building on PFC concepts developed in the existing domestic program.

– Inertial fusion energy (IFE) utilizes advances in lasers, pulsed power technology, and other innovative drivers to achieve fusion at high fuel density. The enormous progress made with indirect drive at the National Ignition Facility, direct drive, magnetic drive Inertial Confinement Fusion (ICF), and heavy ion fusion underpin the promise of IFE. An IFE program that leverages US leadership and current investments should be targeted.

– Breakthroughs in alternate magnetic confinement concepts, beyond tokamaks and stellarators, could lead to a lower cost FPP and subsequently more economically attractive fusion power. Examples include those that require no plasma current, have moderate or zero toroidal magnetic field, and compact, pulsed plasma targets that may eliminate auxiliary heating. A program that supports innovative MFE concepts should be considered.

– Recommendation: Strengthen the innovative and transformative research program elements that offer promising future opportunities for fusion energy commercialization: stellarators, liquid metal plasma facing components, inertial fusion energy and alternate concepts.

Plasma Science and Technology Recommendations

Fundamental plasma science explores new regimes and deepens our understanding of nature. It includes theories that propose foundational descriptions of plasmas, computational methods required to predict outcomes of these theories, and experiments that test the predictions. The knowledge these discoveries provide makes possible the innovative plasma-based technologies of the future. The future of plasma science will rely on consistent support, even when spending for construction projects and larger program elements fluctuate.

– Recommendation: Consistently support fundamental plasma science to ensure a steady stream of innovative ideas and talent; laying the scientific foundation upon which the next generation of plasma-based technologies can be built.

Advances in energy compression with intense lasers and pulsed power facilities have made it possible to squeeze matter to extreme pressures, creating exotic dense plasma states similar to those thought to exist in the interiors of giant planets and stars. However, our ability to diagnose or probe the structure and dynamics of these high energy density (HED) plasmas is inherently difficult due to the very dense and rapidly evolving conditions. Transformational measurement techniques are necessary to develop a physics-based understanding to tackle some of the grand challenges in HED physics that span from Warm Dense Matter (WDM) material properties, to relativistic laser-plasma interactions, to magnetic field generation, to plasma particle acceleration. X-ray free electron lasers can provide such sensitive measurements of HED plasma states that they provide an atom-eye view with attosecond precision, significantly advancing the state-of-the-art. The MEC-Upgrade is the central piece needed to achieve these science goals.

– Recommendation: Complete the design and construction of MEC-Upgrade.

Technologies derived from plasma science investments have had a transformative effect on modern society. The translation of discoveries in low temperature plasmas, for example, has created the semiconductor manufacturing industry as we know it today, providing such advanced electronics as cell phones, laptops and tablets. Plasma-based technologies will continue to improve the quality of life with advances in environmental hazard clean up in air, soil and drinking water, advanced methods for medical treatment and imaging, low-dose X-Ray imaging sources, and electronics. Plasma-based chemical processing has the potential to revolutionize industry by enabling the production of new materials, providing a means to recycle plastics and other wastes. It will address climate change by greatly improving the efficiency of typically energy-intensive chemical processes, and by providing ways to convert carbon-free electrical energy into the products that power society. Translation of basic plasma science research into actual technologies can be accelerated by a more organized and formal investment, including partnerships with industry and other federal agencies, for example, NSF, NIH, USDA, and EPA.

–Recommendation: Establish a plasma-based technology research program focused on translating fundamental scientific findings into societally beneficial applications.

High intensity lasers are opening new fields across plasma physics, from high energy density science and laboratory astrophysics to new diagnostics and particle sources for science and industry. Their unprecedented ability to concentrate power—focusing more power than the world's total electric generating capacity onto an area smaller than the end of a human hair for a fraction of a second—creates unique states of matter with broad applications for fundamental science. Such opportunities were recently highlighted in two reports, the National Academy's *Opportunities in Intense Ultrafast Laser: Reaching for the Brightest Light and Plasma Science*, and in the 2019 Brightest Light Initiative workshop report on ultrafast lasers. A new type of organization needs to be developed to maintain the vitality of this research field in the US and to make available the necessary petawatt-scale and high repetition rate laser technologies. FES has an opportunity to take a leading role in coordinating a high intensity laser research initiative supporting needs in discovery science and advancing energy technologies. Support is also needed for a user network of academic and national laboratory high intensity laser facilities. This would resolve fragmentation where no single national funding agency has responsibility for the field as a whole. Currently funding comes from an array of sources, including DOE FES, DOE High Energy Physics (HEP), DOE Accelerator R&D and Production (ARD&P), DOE National Nuclear Security Administration (NNSA), the National Science Foundation (NSF), and DoD.

–Recommendation: Coordinate a High Intensity Laser Research Initiative in collaboration with relevant DOE offices and other federal agencies.

Advanced lasers that go beyond the state-of-the-art in high peak power and in very high average power (kilowatts and beyond) would open new frontiers in the laser-based science of particle acceleration, advanced light sources, high-field physics and nonlinear quantum electrodynamics, laser-driven nuclear physics, and extreme materials and astrophysics. Competition in this arena is fierce, with scores of multi-petawatt lasers planned in Europe and Asia, and petawatt-class high-repetition-rate laser facilities already in operation internationally. However, the US has an opportunity to stay competitive by leveraging decades-long investments and know-how in laser technology, while combining competencies in multiple emerging technologies (machine learning, advanced manufacturing, diagnostics, and edge computing) to develop a formidable capability that will rapidly accelerate the HED field.

– Recommendation: Pursue the development of a multi-petawatt laser facility and a high-repetition-rate high-intensity laser facility in the US.

Networks provide an organizational structure that supports collaboration by increasing access to experimental facilities, diagnostics, and computational tools. LaserNetUS is an existing very successful model that partially supports facility maintenance and operation, coordinates users, and evaluates proposals. This program provides researchers who would otherwise not have access to state-of-the-art facilities the ability to conduct frontier experiments, enabling workforce development, and facilitating coordination and collaboration. This or a similar model are likely to have a comparable impact in other areas of plasma science and technology, including in low temperature plasmas, laboratory magnetized plasmas, and pulsed power. In addition to access to experimental facilities and user support, networks should include access to resources for computational modeling and diagnostics. Networks provide a mechanism to organize the community input that defines next-generation user facilities.

– Recommendation: Support networks to coordinate research and broaden access to state-of-the-art facilities, diagnostics, and computational tools.

Space and astrophysical plasma physics are enjoying an exciting time of discovery, as advances in spacecraft missions and remote observations provide insights into previously inaccessible regions in the solar system and beyond. The Parker Solar Probe spacecraft is orbiting close enough to the sun to directly measure the solar wind at its origin. The mechanisms by which the solar wind is accelerated and heated are among the most persistent and important open research topics in plasma science. Recent advances in deep space imaging have culminated in the first visualization of an accretion disk, the turbulent, rotating plasma that is generated as material is gravitationally pulled toward a black hole. Understanding this phenomena presents a timely opportunity for FES to establish new laboratory-based plasma space and astrophysics. Controlled laboratory experiments, for example, can isolate, control, and diagnose plasma phenomena responsible for the complex behaviors seen in plasma systems throughout the cosmos. A partnership could be established with NASA in a focused laboratory space/astro plasma physics program, taking advantage of a recent NASA-DOE memorandum of understanding affirming mutual interest in collaborative activities pertaining to energy-related civil space activities. The existing partnership between DOE and NSF could also be leveraged for such an activity, including collaboration on needed facilities in this area. There is a need within the community to advance the capabilities of experiments, including the development of a solar-wind-relevant midscale experiment, to better compliment the advances in spacecraft technology and observation. Laboratory experiments can provide a crucial intermediate between observation and computer simulation as well. In particular, laboratory experiments can provide specific conditions and environments that can be modeled in great detail in simulation frameworks.

– Recommendation: Strengthen support of laboratory-based research relevant to astrophysical and space plasmas through increased programmatic and facility funding as well as expansion of partnership opportunities.

Cross-cutting Recommendations

To successfully carry out this plan, there are foundational research activities that reach across the breadth of the FES portfolio which must be robustly supported. Fundamental theoretical research, separate from computation, remains essential for developing new models, insights, and innovations in topics across plasma and fusion science and technology. This foundational theory work also enables the FES community to continue taking advantage of growth in advanced scientific computing tools that can further improve our fundamental understanding and predictive modeling capabilities, including new methods in Machine Learning (ML), Artificial Intelligence (AI), and Quantum Information Science (QIS). This work is also essential for fusion and plasma research to take full advantage of US investments in exascale computing. A healthy program for developing diagnostics, measurement, and control techniques for a reactor environment and the broader environment of plasmas is equally needed to support progress toward an FPP, as well as toward deeper understanding of plasma science. There is community consensus in favor of increased support for programs to develop critical enabling technologies that advance plasma and fusion science and technology and reduce the cost of resulting applications, including an FPP. In each of these cross-cutting areas, the CPP report identified a wealth of needs and opportunities that should be addressed and pursued.

– Recommendation: Ensure robust support for foundational research activities that underpin all aspects of plasma and fusion science and technology.

Models and diagnostics in many areas of plasma science rely heavily on fundamental data for physical processes such as cross sections and rate coefficients, as well as materials properties such as strength and opacity. These are essential elements of plasma physics and nuclear science which should be more strongly supported. In many instances, models are limited by the absence of accurate input data, rather than knowledge of plasma physics. Research that both supplies and verifies such fundamental data is essential to advance in many areas of plasma science, including development of models. This type of research does not currently have a clear source of funding.

– Recommendation: Support research that supplies the fundamental data required to advance fusion energy and plasma science and engineering.

Budget Scenarios

Plans have been developed for the constant level of effort, modest growth and unconstrained (but prioritized) budget scenarios as described in the charge. While the constrained scenarios require difficult choices, they are constructed to represent a balanced program with prioritization and emphasis on critical elements that advance the fusion energy mission and sustain scientific impact and technological progress. Importantly, the implementation of activities described in the constrained scenarios allows for continued growth should more favorable budgets develop in the future. Nonetheless, the constrained scenarios do not provide sufficient resources to confidently prepare for FPP construction by the 2040s, and large projects in the plasma science and technology area are unfunded. This has consequences as it will cost the US its position as a global leader in fusion energy and plasma science, and compromise future developments with important societal implications.

In all three scenarios, there is a conscious decision to direct resources to the activities identified by the community as the most essential and urgent to enable construction of an FPP. This includes a strategic pivoting toward R&D in fusion materials and technology (FM&T). This pivot is essential because FM&T R&D is on the critical path to an FPP, independent of the eventual choice of FPP plasma core(s). The strategic plan in all scenarios emphasizes innovation in both physics and technology as a means of establishing a unique leadership opportunity for the US fusion and plasma community, and recommends corresponding programs be supported in parallel with facility developments. Following the charge, the scenarios are considered starting from the FY19 budget, specifically focusing on the non-ITER construction project portion. The FY19 budget did not include significant resources dedicated to design and construction of facilities. For this reason, in the two constrained scenarios below, any recommended new construction is funded by redirecting resources from current facility operations and research programs. This redirection is confined within each of the two thematic areas (FST and PST). Table 1 provides a summary of recommended program and facility actions for each scenario.

Portfolio Elements	Scenarios: Constant Level	Scenarios: Modest Growth	Scenarios: Unconstrained	Sustain a Burning Plasma	Engineer for Extreme Conditions	Harness Fusion Power	Strengthen the Foundations	Create Transformative Technologies	Understand the Plasma Universe
Research, Operations, and Small Scale Construction									
FM&T Programs	Yes, enhance	Yes, enhance	Yes, enhance	•	•	•		•	
US Tokamak Operations and Research	Yes, but reduce	Yes, but reduce	Yes	•	•		•		
Stellarator and Alternates Operations and Research	Yes, but flat	Yes	Yes, enhance	•	•		•		
IFE program	Yes, but limited	Yes, but limited	Yes	•					
FPP Design Effort	Yes, but limited	Yes	Yes	•	•	•			
GPS Program	Yes, but reduce modestly	Yes	Yes, enhance				•		•
HEDP Program	Yes, but reduce modestly	Yes	Yes, enhance		•		•	•	•
Plasma-Based Technology Program	Yes, but limited	Yes	Yes, enhance			•	•	•	
Theory and Computation	Yes	Yes	Yes, enhance	•	•	•	•	•	•
New Construction of Midscale+ Facilities									
MPEX	Yes	Yes	Yes		•			•	
FPNS	Yes, but highly delayed	Yes, but delayed	Yes		•			•	
MEC Upgrade	No, but develop further	No, but develop further	Yes		•		•	•	•
EXCITE	No	Yes, but highly delayed	Yes	•	•				
Mid-Scale Stellarator	No	No	Yes	•	•				
BCTF	No	No	Yes		•	•			•
Solar Wind Facility	No	No	Yes				•		•
HHF-Component	No	No	Yes		•				
Multi-PW Laser	No	No	Yes				•		•
High Rep. Rate Laser	No	No	Yes, with partnerships				•	•	•
Midscale Z-Pinch	No	No	Yes, with partnerships				•		•
VNS	No	No	Concept Study			•			
Collaborations and Networks									
ITER research team	Yes	Yes	Yes, full	•	•	•			
Private fusion collaborations	Yes, enhance	Yes, enhance	Yes, enhance	•	•			•	
International fusion collab.	Yes	Yes	Yes, enhance	•	•			•	
LaserNetUS	Yes	Yes, enhance	Yes, upgrade				•	•	•
ZNet, MagNetUS, LTPNet	No	Yes, but limited	Yes				•	•	•

In the constant level of effort budget scenario, formation of a nascent ITER research team and FPNS design are initiated immediately. FPNS construction should commence as soon as possible and would likely need to start in the second half of the decade with operations not beginning until the 2030s. Establishment of EXCITE mission need and initial design should also proceed immediately. Although EXCITE construction costs likely cannot be accommodated within this scenario, it is vital to develop a conceptual design, and if possible, a full construction-ready design in the event budget outlooks improve. Additional options to help close the integrated tokamak exhaust and performance (ITEP) gap, including enhanced collaboration with private companies and international partners, must be developed as well. Increased investments in FM&T enable significant growth in programs (including blanket and tritium breeding research), completion of MPEX on schedule, the buildup of a domestic collaborative FPP conceptual design effort in the early 2020s. FM&T investment also allows the construction of a high heat flux coupon-scale testing facility for PFC development in the second half of the 2020s.

The increased emphasis on these FM&T activities requires a reduction in tokamak research and operations, which are being used to resolve FPP design gaps in the areas of disruptions, burning plasma physics, plasma-facing materials, and operating scenarios. In particular, a modest but immediate reduction in operations funding to the existing major tokamak facilities (DIII-D and NSTX-U) would be required, with a more significant reduction (~50%) in the mid-2020s, likely resulting in the cessation of operations of one of the major tokamak facilities. The continued growth of the ITER research team and expanded private and international collaborations provides increased access to the burning plasma regime and helps offset the reduced research effort on the existing facilities. This pivoting of tokamak research and facility utilization should proceed at a pace which enables total tokamak research funding to continue at a stable level, with changes in facility emphasis and timing clearly communicated in advance to avoid significant workforce continuity challenges. A more aggressive ramp down of existing facilities (DIII-D and NSTX-U) and programs was considered, but it was concluded that this approach would only marginally advance timelines at the expense of losing workforce expertise deemed essential to closing the ITEP gap, and would delay closure of the remaining tokamak physics gaps.

Foundational research activities in theory, modeling, and measurement innovations, together with all other existing program priorities (including INFUSE, stellarators, liquid metal PFCs, RF technologies etc.) continue to be supported at current levels in this scenario, and these should similarly pivot toward FPP relevant needs. A modest IFE program, focused on developing enabling technologies, is supported in this scenario through redirection of existing HEDP funds.

Preconceptual development of facilities that are not started within the 10-year horizon of this charge (e.g. mid-scale stellarator, blanket component test facility or volumetric neutron source) are also supported. It is important to note that the technology readiness levels of the required elements for an FPP would likely remain low, creating significant risk in proceeding with an FPP in the 2040s.

In the PST portfolio of activities, FES should maintain its level of commitment to funding single-PI researchers, to operations of collaborative research facilities, and to LaserNetUS. FES should specifically form a program focused on Plasma-Based Technology by transitioning support for similar research currently funded through the centers and the NSF-DOE partnership. It is important for FES to continue to develop pre-conceptual plans for new facilities and articulate the mission needs while at the same time planning for future upgrades to existing facilities. Funding for these activities would be modest, consistent with identifying R&D needs to bring facility planning to the next critical decision level, and be redirected out of current plasma science facility or experimental user support. In the case of the MEC-Upgrade, a small level of support similar to current funding levels should be extended for pre-project R&D and project planning to reduce the risk associated with entirely new technologies.

Additionally, FES should encourage community organization toward new networks in the areas of magnetized plasma laboratory research (MagNet), pulsed-power plasma research (ZNet), and low-temperature plasma science (LTPNet). Under a constant level of effort budget scenario, this activity will be limited to improving communications and sharing of resources within the research community. Particularly in a constrained scenario, it is imperative that FES reaffirm its commitment to funding agency partnerships including NSF, NNSA, and ARPA-E, as well as explore the potential for new partnerships with other NSF divisions and directorates, NASA, NIH, ONR, DOE BES, and AFOSR.

It is important to emphasize that within the constant level of effort scenario, the new initiatives and pivoting of program elements are only achieved at great cost to existing areas of US strength, and many time-critical opportunities for future innovation, impact, and leadership are missed. The pivot to increased FM&T research is vital for the fusion energy mission, but it cannot proceed in this scenario at a pace sufficient to be confident in FPP readiness by the 2040s. Likewise, establishing a new plasma technology program requires reductions of other vital plasma science and technology research thrusts. In this scenario, the opportunity to build MEC-upgrade is lost, initiation of EXCITE construction is highly unlikely, and the US tokamak program is significantly reduced. Many additional opportunities for innovation throughout the portfolio, including a number of possible PPP opportunities, cannot be acted upon. And although some domestic tokamak research can be redirected to ITER and collaborative efforts on international and private facilities, the resources to take full advantage of these opportunities are not available, and possibilities for US leadership are inherently limited on international facilities not predominantly funded by the federal program. Therefore, while these recommendations help align the FES program with the technology and science drivers, the ability to act with urgency, enable innovation, and drive US leadership in this scenario is highly constrained.

In the modest growth (2% above inflation) scenario, the FPNS schedule is accelerated by 2–3 years, with operations targeted to begin by the end of the 10-year period of this plan. The related structural and functional materials programs are also expanded. Significant funding becomes available to accelerate the effort on the ITEP gap in the latter half of the 2020s, which may enable construction of the EXCITE facility to begin, as well as possible alternate approaches including major upgrades to an existing facility and/or more aggressive pursuit of collaborations. An expanded ITER research team also becomes possible in the later 2020s. With modest growth, the technology and science drivers are significantly advanced by more robustly funding research programs in GPS and HED. Additional investments in enabling technologies are made that support plans for new facilities needed to move the field forward. Cross-cutting research that connects topical areas such as multi-scale simulation codes, advanced computing, and diagnostic development, should be better supported to provide increased impacts across the FES portfolio. Small enhancement projects to the existing PST facilities and networks are pursued to extend their lifetime and increase their availability. Even small investments in new Network coordination (e.g. LTPNet and MagNet) will enable leadership in these areas. Other strategic advancement of existing and modest scale new programs can be evaluated and executed consistent with the recommendations in this report, the priorities listed below, and the guidance from the CPP report. Given that much of this advancement could happen in the later 2020s, future long range planning activities will also be able to provide more detailed guidance for prioritization.

The return on the investment of the relatively small increment from the constant level of effort to the modest growth scenario is substantial. It accelerates the fusion energy mission and provides excellent science per incremental dollar by continuing to support the high-impact work being done across the program. Furthermore, it aids the development of emerging technologies and innovative R&D to ensure continued progress, while also looking toward new facilities that will be forward leaning when they are built. However, there are still significant costs incurred and opportunities missed in this scenario. Most notably, meeting the goal of FPP readiness by the 2040s remains highly unlikely, significant reductions to the US tokamak program are still required, and some important time-sensitive opportunities for US leadership such as construction of MEC-Upgrade cannot be acted upon.

In the unconstrained, but prioritized, scenario, the FPNS facility is accelerated further, with operations anticipated in the latter half of the 2020s. A number of additional facilities and program enhancements have been identified that take advantage of the opportunities provided by the full breadth and creativity of the program. The following facilities and their supporting research programs are recommended, in prioritized order, factoring in the timeliness and urgency of the activities in supporting the strategic plan:

1. At equal priority:
   - Design, construct, and operate EXCITE by 2030 to close the integrated tokamak exhaust and performance gap.
   - Construct and operate the MEC-Upgrade to enable cutting edge science in laser-plasma interactions, warm dense matter, and dense material physics via the co-location of a high energy and high repetition rate lasers with an X-ray free electron laser (XFEL).
2. Design, construct and operate a new Stellarator facility to demonstrate theoretically predicted advantages of an optimized stellarator configuration.
3. Design, construct and operate a Blanket Component Test Facility to perform non-nuclear testing of integral scale blanket components.
4. Design, construct and operate a new Solar Wind Facility to investigate the fundamental processes in magnetized, high-beta plasmas relevant to, e.g., accretion disks and stellar winds.
5. Design and begin construction of a Component-level High-heat Flux Testing Facility for plasma-facing component (PFC) development.
6. Construct and operate a large-scale multi-petawatt laser facility for novel studies in high field physics and the exa-Pascal pressure regimes.
7. Design, construct and operate a high repetition rate laser facility for precision studies of complex high energy density phenomena, potentially in collaboration with other agencies.
8. Design, construct and operate a mid-scale Z-Pinch facility for magnetized high energy density plasma studies, potentially in collaboration with other agencies.

As emphasized above, programs should be grown as needed to support all facility research and operations activities. Beyond providing the appropriate support for facilities, the following new or expanded programs are recommended in priority order:

1 At equal priority:

– Strengthen FST programs (structural and functional materials, blanket and tritium fuel cycle, magnet development, and solid and liquid PFCs), increase support for research and operations on existing tokamaks in the early 2020s, and ensure optimal support of the national FPP design effort.

– Strengthen programs in GPS and HED to optimize progress and discoveries (consistent with priorities expressed here and within the CPP) in frontier plasma science and the plasma universe.

2 Strengthen support for the plasma-based technology program, with significant expansion in the number of grants, establishment of multiple technology-related centers, and a robust technology transition program.

3 Strengthen additional fusion science programs to optimize progress (stellarator physics, heating and current drive (H&CD) technologies, balance of plant technology), and ensure optimal support of the ITER research teams in the mid to late 2020s.

4 Increase operations support and aggressive upgrades to the LaserNetUS network to expand the base of users while allowing for a diverse set of capabilities that maintain US competitiveness.

5 Establish a program to develop innovative fusion core concepts using rigorous evaluation and metrics.

6 Expand the IFE program to more aggressively pursue IFE requirements and technologies.

7 Explore options for component-scale irradiation testing in a volumetric neutron source (VNS).

8 Strengthen and expand networks to coordinate and leverage researchers and facilities in pulsed power, basic magnetized plasma experiments, and low temperature plasmas.

These new and expanded programs should be pursued as feasible within a given budget scenario, balanced against the new facility recommendations using the prioritization criteria expressed throughout this report. With this scenario, all necessary elements could be advanced to the appropriate technology readiness level to enable a fusion pilot plant by the 2040s. Clearly, this scenario grows the FES program significantly beyond the constant level of effort or modest growth scenarios. However, with careful staging of new facility construction, program pivoting, and aggressive utilization of public-private partnerships, we believe that much of what is recommended in this scenario can be accomplished in a timely manner and under realistic budgets.

Appendix

Appendix A: Public Private Partnerships

Introduction

Public-private partnerships (PPP) are highly recommended as a means of rapidly and efficiently enhancing scientific and technological capabilities. Both general and fusion-specific plasma science and technology programs will benefit from robust PPP collaborations. Scientific insights gained from basic and applied plasma science research lead to innovations that ultimately are developed into technologies in partnership with industry. Strategic partnership between public programs and private activities can provide an effective approach to resolving common technical problems facing fusion and plasma science in creating a competitive energy source in the US market, as well as new technologies utilizing plasma processes. Because the nature and missions of the private companies in basic plasma science and fusion energy development differ, and the breadth and maturity of existing PPP programs also differ, the PPP mechanisms for each area are described separately.

Fusion Science and Technology

There is broad agreement across stakeholders that it is in the best interest of the DOE and the nation to have commercial fusion energy generation developed and based in the US. The fusion energy endeavor is receiving new and significant contributions from private entities that aim to address the clean energy market. There are currently 22 private entities that have raised nearly $2B in private capital to develop fusion energy concepts, with some targeting commercialization by the 2030s. Partnership between the public program and private activities can provide an effective approach to resolving common technical problems facing fusion as a competitive energy source. Although public and private strategies differ in technical focus and deliverables, significant overlaps exist that are beneficial to both parties and can accelerate progress toward the common goal of bringing fusion power to the grid.

Many private fusion companies are preparing to build facilities to demonstrate that their technologies scale, can be integrated, and can produce fusion-power relevant plasmas. Examples include DT burning plasmas, next generation spherical tokamaks, high temperature field reversed configurations, high current pinches, compact stellarators, spheromaks, converging plasmas, impactors, and laser-driven IFE ignition, all aiming toward design of full-scale power plants. International competitiveness is an important consideration in the identification of candidate public-private partnership (PPP) programs, given that the UK, Europe, China and other countries are supporting development of their burgeoning domestic fusion industries. An Electric Power Research Institute (EPRI) report describing the responsibility of government and industry in the development of fission nuclear power showed two salient points are: 1) the significant

Program on Technology Innovation: Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors, EPRI 2017 Technical Report, EPRI Project Manager, A. Sowder; https://www.epri.com/research/products/3002010478

scope of shared partnership and responsibility between government and industry in establishing a new type of energy generation technology, and 2) the gradual transition from government-led to industry-led activities approaching and realizing commercialization. This provides a positive indication for the public-private partnership on facilities from a similarly complex technical system development.

Candidate public-private partnership programs can take different forms based on the maturity and mission of the technology, in addition to the capital required. The DOE currently has PPP programs to aid in the maturation of low TRL technologies and is considering other programs, including a milestone-based cost-share program to demonstrate fully integrated mid-TRL technologies. With 22 members of the Fusion Industry Association (FIA) engaged in at least one of the strategic objective or program recommendation topics from the CPP report, there exists significant potential for partnership with the public program to close gaps on these technical topics of mutual benefit.

Low TRL Maturation Programs: Existing technology maturation programs have been successful and should be expanded to enhance the scope and scale for closure of key technology gaps. Examples are the ARPA-E ALPHA, ARPA-E BETHE, ARPA-E GAMOW, INFUSE, and the SBIR/STTR programs. These were established to both help mature specific private industry fusion energy concepts, and to develop widely applicable platform technologies that would be useful across many fusion energy concepts. The high degree of interest from the private sector in programs like INFUSE has been evident since many more applications from private companies were received than could be funded. Given industry demand, additional resources in these programs would enable private fusion activities to grow and even accelerate.

- ARPA-E ALPHA create tools to develop lower cost pathways to fusion energy
- ARPA-E BETHE deliver higher maturity, lower cost fusion technologies through concept development of less mature concepts, component development of mature concepts, and capability teams to accelerate development of all concepts
- ARPA-E GAMOW prioritizes R&D in technologies between fusion plasma/balance of plant, high-duty cycle drivers, and cross-cutting areas such as materials and additive manufacturing
- INFUSE accelerates fusion energy development in the private sector by reducing impediments to collaboration involving the expertise and unique resources available at DOE laboratories
- SBIR/STTR develops innovative techniques, instrumentation, and concepts that have applications to industries in the private sector

As the possibility for commercialization grows, partnerships where industry may bear a greater burden of the cost become advantageous. Completion of prototype products can be made more quickly as private companies driven by market needs focus on fast and efficient product delivery. A milestone-based 50/50 cost share program should be created for partnerships to develop enabling technologies that are of larger scale than projects funded through INFUSE, ARPA-E, and the SBIR/STTR paths. Such a program could target the development of specific components or enabling technology for the fusion program. Examples could include magnets, high-power microwave and radiofrequency sources, neutron sources for materials irradiation, systems for tritium breeding blankets and tritium processing and plasma facing components. Some of these technologies could have applicability beyond fusion, for example superconducting magnets and cables have broad commercial applicability in fields such as energy transmission and medical imaging. A cooling technology that can demonstrate power handling of greater than 10 MW/m² as needed for tokamak divertors may also be applicable to other applications where energy is concentrated such as high energy particle accelerators or heat removal from advanced semiconductors.

Integrated Facility Cost Share Program: We support the concept of a milestone-based cost share program aimed at the demonstration of integrated facilities with the potential to more rapidly and cost-effectively close technological gaps to achieving fusion energy. Such an activity should be executed as a parallel investment to augment the public long-range plan. This approach would maintain a robust strategy in the federal program while supporting high-risk, high-reward private industry efforts to allow “multiple shots on goal” in the effort to develop fusion energy.

An example of a new fusion-centered milestone-based cost-share program with private industry was recently proposed by the FIA, seeking near-term investment in order to be relevant for current commercial timelines. The program is based on the NASA Commercial Orbital Transportation Services (COTS) cost share program. This program, targeting partnership with private industry to take over more routine operations in low-Earth orbit, proved to be successful in delivering a space launch vehicle at a ~ 90% lower cost than the public program. In this case NASA knew how to accomplish launches to low Earth orbit; nonetheless, industry innovated with new technologies and approaches which demonstrated more cost-effective solutions. Due to the success of this program, this approach is being applied by NASA and other agencies to lower TRL technologies. In the FIA-proposed fusion milestone-based cost share program, DOE would leverage private sector creativity to field new US-based capabilities, enabling fusion commercialization and research access to new user facilities. This program would be driven by the market needs, leveraging the focus private companies provide for fast and efficient product delivery. Each private sector participant would meet the milestones agreed upon with DOE to receive the public funds in a proposed 50/50 cost share fraction. This would follow a portfolio approach which has multiple awardees in a competitive process. Details should be worked out between DOE and industry stakeholders so that programs could begin as soon as possible.

Facility development and shared programs: The FST program needs new experimental facilities that can close the program gaps in a timely fashion; private entities can help where mutually beneficial activities are identified. Including private sector input in the design of these facilities has the potential to reduce both costs and development time by leveraging private sector efficiencies and practices. DOE can also look to other PPP models, such as the approach utilized for the DOE Advanced Reactor Demonstration Program. In addition, private access to operating public sector facilities and vice-versa can provide an efficient method to close technical gaps of mutual interest. Generally speaking, the public program should seek to procure available capabilities and equipment from the private sector.

Information Access: In order to best equip the public and private sectors for success, FES-funded programs should strive to make information available between parties. A pathway for information transfer from public to private should exist for public programs. For example, access to ITER design information should be provided to US domiciled companies by FES. This access will help leverage the investments made and technological developments that are occurring and maximize the US investment in ITER. Similar responsibilities lay with private entities that participate in public private partnerships. Clear delineation of intellectual property protection should occur as programs are formed, under the expectation that progress, milestones, and discoveries will be shared whenever possible. Coordination of efforts between all parties might best be made by consolidation within the FPP pre-conceptual design effort to minimize duplication of effort and advance the pace of discovery.

Mature Stage Programs: New PPP programs to further aid in the commercialization of fusion energy should be considered. The most aggressive private industry plans seek to put fusion power on the grid in the early 2030s. If these companies succeed, mature stage PPP programs will be needed in advance of the groundbreaking for the power-producing facilities, which could occur as soon as the mid-to-late 2020s, i.e. within the timeframe of this strategic plan. For example, loan guarantee programs have been used to help deploy several successful large-scale energy projects through the DOE Loan Programs Office. DOE could also consider the development of a long-term power purchase agreement program, which would simplify financing for the future private sector fusion power facilities.

Plasma Science and Technology

Basic plasma science research discoveries can lead to innovations that allow US industries to maintain global leadership. Historically, insight gained from basic plasma science has led to many societally important contributions. Plasma accelerators offer practical applications for cancer treatment and diagnostic imaging. Atmospheric pressure plasmas are transformative, transferring green-energy-derived electricity to electrons and ions in gas or liquid phase for the purpose of chemical processing, the treatment of disease, water and air purification, material processing, and light production. Advances in low pressure multi-frequency RF discharge technology can position the US industry to maintain leadership in semiconductor manufacturing.

The semiconductor industry is an instructive example of how partnerships between universities, government and industry can come together and successfully revitalize a field. Here plasma science plays a key role in the processing of semiconductor devices. In the 1980s, the US had fallen behind in semiconductor manufacturing. The establishment of the Sematech consortium, a partnership between 14 US semiconductor companies and the federal government, focused on improving manufacturing capability. The consortium enabled the US to reclaim its leadership role and now leads globally with nearly 50% of the market share.

An ecosystem that provides a pathway for partnering with industry and transferring plasma science innovations does not exist beyond the DOE STTR/SBIR program. Vehicles that facilitate such partnerships are necessary for continued innovation by bridging the gap between science discovery and forming of new technologies. Such partnerships also allow for the resolution of ongoing and arising engineering problems in industry through applied research. The need for public private partnerships in the semiconductor arena in particular was highlighted in the 2020 Decadal study where it was suggested that a private public incubator be established that prioritized research particularly focused on breakthroughs in the 5–10-year timeframe to strengthen US leadership in this trillion-dollar market. It would involve collaborative activity between academia, startups and established companies with the end goal of maturing research and disruptive breakthroughs for the purpose of commercialization.

Shared research programs: Research consortia that bring together public and private sectors to solve common technical problems should be encouraged. Currently, we stand at the precipice of an exciting era in plasma science and technology where fusion and plasma research offer potentially transformative applications. As industrial applications grow, the potential for research consortia has grown, included partnerships between private companies and universities to solve common problems. With Sematech as the exemplar, new areas for collaboration abound, such as:

- Control of atmospheric pressure plasmas for the purposes of chemical processing, the treatment of disease, water and air purification, and light production
- Advances in low pressure plasma discharges to improve semiconductor manufacturing
- Plasma accelerators that offer practical applications for cancer treatment and diagnostic imaging

Questions raised in private industry that are fundamental and not aligned with commercial goals are often left unanswered. Researchers in universities are well suited to address foundational issues that may not have immediate applicability to any one particular company. By pooling resources, public-private consortia may share the burden and reward.

Shared research programs can also serve to shepherd scientific discoveries derived from FES-funded research to technological implementation either through start-ups or licensing. The model suggested here is akin to that utilized in the NSF. The NSF Partnership in Innovation (PFI) program provides a funding vehicle for single investigators to carry out customer discovery and develop technology based on prior research. Such programs provide a framework partnering researchers with industrial entities interested in the development of the technology.

Additionally, the current FES SBIR/STTR program should be leveraged for better alignment with mission goals. FES should convene a community workshop that brings together university, national laboratories, and the private sector to outline research needs in order to focus the program on market driven technologies. In this way, the program is responsive to new developments and opportunities. This approach is in contrast to the current approach where SBIR/STTR grants and contracts are awarded separate from FES priorities.

Altogether, to maintain competitiveness, a framework is required that facilitates the transfer of technology derived from DOE-funded PST research into innovations that will impact society. We propose that the recommended newly established Plasma Science and Technology program contain vehicles that support PPP options including single investigator innovation development and partnering with industry to address technical challenges that impact overall US global leadership.

Summary

Development of public-private partnerships is recommended as a new paradigm for appropriately chosen program elements. To maintain and enhance competitiveness, a clear framework is required to facilitate developing FES-funded research into societally impactful innovations. The programs described above have all been demonstrably successful where applied and should be implemented within FES. Initiatives are proposed to leverage shared public-private interests for maximal mutual benefit. Appropriate resources should be provided for these programs so that strong partnerships may be established. Regular sharing (e.g. annual or biennial) of information is important so that public programs remain adaptable and private programs might benefit from public accomplishments. Growth of PPP programs will encourage the public and private sectors to work closely together to more rapidly develop fusion energy and plasma technologies for the betterment of the US and the world.

Appendix B: DEI, Workforce, and Outreach

The success of this strategic plan requires innovation, creativity and a talented, multidisciplinary and diverse workforce. This appendix seeks to enable this required workforce by detailing actions that can be taken to achieve a more diverse, equitable and inclusive (DEI) environment and growth of the needed workforce. The Community Planning Process (CPP) report presented consensus views on needs in these areas. Quoting from that report:

"Diversity is expressed in myriad forms, including all ages, socio-economic backgrounds, ethnicities, genders, gender identities, gender expressions, national origins, religious affiliations, sexual orientations, family education level, disability status, political perspective—and other visible and nonvisible differences. Equity ensures equal opportunity and the impact of those opportunities in equitable outcomes for all persons; requiring zero tolerance for bias, harassment, and discrimination. Inclusion is the deliberate effort to ensure that our community is a place where differences are welcomed and encouraged, different perspectives are respectfully heard and where every individual feels a sense of belonging."

Data show that the fusion and plasma science research communities have significant deficiencies in workforce diversity, with participation from women and underrepresented minorities below national averages for other subfields of physics and engineering. This means we are not accessing the available talent pool in our current workforce, a clear barrier to our success. The problems do not stop with recruiting talent into the field as retaining diverse talent in the field is affected by the culture within the community. A community that is not welcoming and supportive to diverse populations will have a hard time retaining those populations. Embracing equity and inclusion is the key to addressing this issue.

A recent policy change by the Office of Management and Budget placed significant limits on workforce and outreach programs at DOE. This policy was well intended, targeted at reducing duplication of education and outreach activities at federal agencies, but had the unintended consequence of eliminating discipline-specific outreach and workforce programs that were not being duplicated at other agencies. Specifically, this eliminated an important graduate fellowship program and placed limits on undergraduate research programs executed by DOE. DOE has been able to continue to offer opportunities for undergraduates through the Science Undergraduate Laboratory Internships (SULI) program, which is an excellent program that brings undergraduates to national laboratories for research experience. What was lost was a broader undergraduate research program that placed undergraduates at a wide range of institutions, including universities and industry, where they could participate in a wider spectrum of FES research activities. DOE has created a new program, the Office of Science Graduate Student Research (SCGSR) Program, that provides resources to enable graduate students to spend a portion of their graduate program working with a mentor at a national lab. This program is very useful, but does not replace the former graduate fellowship program. The SCGSR can not be utilized as a tool to recruit graduate students into the field; it helps students already committed to working in the area in obtaining access to cutting edge facilities and national lab researchers to complete their thesis work. A graduate fellowship program can target a diverse population of undergraduate students and be used as a tool to recruit them into areas supported by DOE with workforce needs.

The following sections detail actions that FES can take to address DEI, workforce and outreach needs. Though listed separately, all three areas tie together strongly: effective expansion of the fusion and plasma science workforce requires tapping into the full available talent pool, which better reflects the diversity of gender, background, and identity, as well as enacting policies aimed at improving the social climate within the community and institutions to increase retention overall. The dual efforts of improving DEI and developing workforce, in turn, stem from an effective outreach effort that spans all stages from energizing the imagination of K–12 students and the general public, to directly attracting undergraduates and graduate students into the field, to expanding and retaining plasma and fusion faculty presence at colleges and universities throughout the nation. In addition, there are significant opportunities for recruitment of established scientists and engineers working in areas other than fusion and plasma into the community, in both the federal program and private fusion and plasma-focused companies. Progress on any one of these fronts will be effective in improving all three desired outcomes.

Since the CPP report was community-based, many of the recommendations are aimed at the fusion and plasma science research community as a whole rather than to any one funding agency. The CPP report made a number of recommendations on DEI and workforce, all of which should be acted on. Here we have identified specific recommendations that are actionable by DOE or otherwise within the federal government. We call out a second set of recommendations that DOE could advocate for in partnership with other federal agencies and research institutions.

Recommendations that are actionable by FES

Diversity, Equity and Inclusion (DEI)

For a diverse, equitable and inclusive environment in the field of fusion and plasma science and technology, we recommend the following actions:

- Unwarranted conscious or unconscious bias (based on gender, race/ethnicity, or other personal and scientifically-irrelevant characteristics) can interfere with a fair and equitable funding process, and should be discouraged by FES-funded programs. This impact can be minimized, for instance by implementing double blind peer-reviewing of proposals. Similar review processes have been successfully implemented in other agencies, such as NASA and NSF.
- Policies that promote work-life balance are essential towards achieving better gender and financial-background equality and will improve the diversity of the workforce. While we understand that FES has limited power in implementing parental leave policies and the topic is part of a broader national conversation, FES can take further action to accommodate parenthood among its funding recipients. For instance, FES should work with PIs to adjust milestones and deliverables to accommodate research team members who take family leave. FES has already adapted deadlines due to the exceptional conditions during COVID-19, proving that the avenues for these deadline adaptation exist.
- Among equally competitive proposals, the committee believes that DEI and workforce improvements should weigh into the awarding process. This can be achieved by implementing an additional requirement in proposals for the consideration and promotion of DEI efforts as an integral aspect of the review process for institutions seeking federal funding from DOE OFES. Successful examples of similar actions exist, such as the requirement for addressing “broader impacts” in proposals submitted to NSF.

Workforce development

In order to attract the best talent and recruit individuals with the skills that the program needs, as well as to retain them and grow our workforce:

- As recommended in Chapter 2: Restore DOE's ability to execute discipline-specific workforce development programs that can help recruit diverse new talent to FES-supported fields of research. We recognize that this requires action beyond DOE.
- Reinstate or create fellowships to help recruit and retain the best students into FES research areas, including a diverse applicant pool. Fellowships for new graduate students are critical to recruitment. Expanded support should be provided to directly support students and postdocs during their tenure (such as internships and SULI for undergraduate and SCGSR for graduate students) and for early career scientists (such as the DOE Early Career Research Program). These programs improve recruitment, facilitate collaboration, and mitigate imbalances of power. Programs should emphasize broadening the recruitment pool and opportunities for women and underrepresented minorities. They should support work at National Laboratories, Universities, and private companies.
- Expand or create programs that aim to increase and better retain faculty lines at universities and colleges, including faculty start-up grants to incentivize departments to grow their existing fusion or plasma science faculty numbers or to start such a program outright. While existing Early Career Awards (ECAs) support new junior faculty, no program currently exists within FES to encourage colleges or universities to hire fusion or plasma science faculty in the first place. Such programs have been successfully implemented at other funding agencies (e.g. NSF's Faculty Development in the Space Sciences Program). Such a program can also address equity and diversity by expanding and aiming such efforts at Historically Black Colleges and Universities (HBCUs), Tribal Colleges and Universities (TCUs) Program, and Hispanic Serving Institutions (HSIs). Efforts to support retention of faculty should also include expanding ECAs to non-tenure faculty at universities and implementing joint university/national lab faculty development programs.

Outreach

Recruiting the best workforce requires reaching out to a broad sector of the public, at every educational level. While we are aware of the limitations imposed by OMB regulations, we request FES to support outreach to attract a diverse future workforce and publicly promote the role of plasma and fusion in society.

There is an opportunity to use FES resources to promote plasma science, and in particular fusion science. These actions should come from FES, given that NSF does not currently support fusion science research or outreach, and thus the only fusion associated outreach can be conducted by national labs. The goal of these outreach activities is to create a broad entrance to the plasma and fusion science and technology workforce pipeline, which will enable access to the diversity (in skill-set and beyond) required to execute the program.

These FES resources can be used to support the development of a new public-facing website for plasma science and fusion (potentially in collaboration or coordination with existing resources). Such resources could also support pre-college outreach to engage the youngest minds with the FES program and inspire students to consider careers in plasma and fusion science. The latter could include student design competitions, which have proven successful for the promotion and attractiveness of other fields (e.g., NASA).

Actionable via collaboration or other agencies and institutions

In addition to the actions directed to FES, the committee encourages FES to engage with other federal agencies and stakeholders on DEI and Workforce development recommendations laid out in the CPP report that are not directly actionable by FES alone.

- Institutions should engage Diversity, Equity, Inclusion (DEI) Experts to advise our community and develop assessment tools. Such programs, such as that led by APS-DPP, exist and have already been successfully implemented in FES funded institutions.
- FES-funded institutions and events should adopt or update Policies and Codes of Conduct, including articulating and adopting codes of conduct for meetings; requiring training on bias, cultural competence and bystander intervention; and investigating how to assess reports of harassment. In its implementation,for instance, a Code of Conduct could be required for all DOE funded workshops and events.
- DOE, and FES-funded institutions should create an accessible environment for all members of our community (in national laboratories and in universities, respectively). All institutions funded by or working in fields of FES should also expand recruitment pools (geographically, fields of study, types of institutions, etc.) and identify currently underrepresented areas with linkages to the work-force development topics outlined above.
- Create Parental Leave Policies: in addition to direct FES action as indicated above, FES should work with institutions on more uniform family leave policies across institutions to economically support up to 12 weeks of leave taken under the protection of the Family and Medical Leave Act, allowing continued support for personnel during Principal Investigator leave, supporting flexible hours and telecommuting, and access to lactation space.
- Institutions funded by or working in fields of FES should develop flexible post-undergraduate education options and facilitate employment of scientists and engineers with BS/MS degrees at FES facilities and BS/MS development programs.

Appendix C: Charge Letter

Department of Energy
Office of Science
Washington, DC 20585

30 November 2018

Dr. Donald Rej
Chair, Fusion Energy Sciences Advisory Committee
Program Director, Office of Science Programs at LANL
Los Alamos National Laboratory, MS-A121
Los Alamos, NM 87545

Dear Dr. Rej:

This letter requests that the Fusion Energy Sciences Advisory Committee (FESAC) undertake a new long-range strategic planning activity for the Fusion Energy Sciences (FES) program. The strategic planning activity—to encompass the entire FES research portfolio (namely, burning plasma science and discovery plasma 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.

In developing recommendations within this long-range strategic planning activity, FESAC should take into account the following aspects:

- Identifying specific research areas, across the entire FES portfolio, in which the U.S. should establish or enhance global leadership.
- Maintaining a healthy and flexible program, which incorporates the roles and contributions of universities, national laboratories, and industry, to deliver science results throughout the next decade.
- Maintaining, upgrading, and/or pivoting current small-, mid-, and large-scale facilities, including DIII-D and NSTX-U, and also initiating new experiments/facilities/projects.
- Identifying international collaborative opportunities or partnerships that can give U.S. scientists access to devices outside of the U.S. with unique capabilities.
- Providing support for private-public partnership ventures.
- Positioning the U.S. to obtain maximum benefits in the ITER burning plasma science era.
- Considering the future budgetary constraints described below, as well as the technical readiness and feasibility for any activity to proceed.

Your report should provide recommendations on the priorities for an optimized FES program over the next ten years (FY 2022-2031) under the following three scenarios with the FY 2019 enacted budget for the FES program as the baseline:

- Constant level of effort (defined as the published OMB inflators for FY 2022-2031)
- Modest growth (use 2% above the published OMB inflators)
- Unconstrained budget: For this scenario, please list, in priority order, specific activities (beyond those mentioned in the previous budget scenarios) that are needed to achieve and maintain a leadership position addressing the scientific opportunities identified by the community.

Within each of the three scenarios, assume that the U.S. Contributions to ITER project will continue through this entire period.

You should consider these three budget scenarios as an opportunity to identify priorities and make high-level recommendations. The activities that you recommend should be (to some significant extent) implementable under reasonable budgetary and programmatic assumptions. At the same time, the budget scenarios should not drive the prioritization to the degree that research/projects are promoted solely for their ability to fit within an assumed profile.

The FESAC report should articulate the scientific opportunities that can and cannot be pursued, as well as the approximate overall level of support needed in the FES program to pursue these opportunities within the various funding scenarios identified above.

The FESAC activity in addressing this charge should commence after the completion of community-led activities to provide broad input to this long-range planning. This two-phase approach for long-range planning is similar to that used by both the High Energy Physics program and also the Nuclear Physics program within the DOE Office of Science.

For the first phase, we have asked the American Physical Society's Division of Plasma Physics (DPP) to lead with the organization of community-led activities (such as discussions, town halls, workshops, and any other forums it chooses). We want the community to be actively involved in this long-term planning process. We are grateful that the DPP leadership is willing to provide this valuable sponsorship of the community-driven first phase.

The second phase of the process involves this charge to FESAC. Although this charge will be discussed at the December 6 and 7 FESAC meeting, no FESAC subcommittee to address the charge will be formed at that time. Toward the end of the community's process to develop its important input for planning, a FESAC subcommittee shall be formed to carry out the work of developing the long-range plan.

We would appreciate receiving the report from FESAC by December 2020, if possible. We understand that this is a challenging task; however, your considerations of these issues will be essential input to DOE planning. Please let us know if there is anything we can do to help you in this process.

Sincerely,

J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Appendix D: Committee Membership

Troy Carter, chair
University of California, Los Angeles

Scott Baalrud
University of Iowa

Riccardo Betti
University of Rochester

Tyler Ellis
Commonwealth Fusion Systems

John Foster
University of Michigan

Cameron Geddes
Lawrence Berkeley National Laboratory

Arianna Gleason
SLAC National Accelerator Laboratory

Christopher Holland
University of California, San Diego

Paul Humrickhouse
Idaho National Laboratory

Charles Kessel
Oak Ridge National Laboratory

Ane Lasa
University of Tennessee, Knoxvillle

Tammy Ma
Lawrence Livermore National Laboratory

Rajesh Maingi
Princeton Plasma Physics Laboratory

David Schaffner
Bryn Mawr College

Oliver Schmitz
University of Wisconsin, Madison

Uri Shumlak
University of Washington

Lance Snead
Stony Brook University

Wayne Solomon
General Atomics

Erik Trask
TAE Technologies

Francois Waelbroeck
University of Texas, Austin

Anne White
Massachusetts Institute of Technology

Don Rej, ex officio
Los Alamos National Laboratory, retired

Appendix E: Process and Meetings

This report is the culmination of a two-year, two-phase strategic planning process. The first phase, the Community Planning Process (CPP), was the primary mechanism for all members of the community to provide input. In the second phase, the FESAC Long Range Planning study, we used the CPP report as a starting point. The sub-committee sought a variety of additional inputs from the community and other sources during our 10 month study. This included community focus groups and workshops and briefings from a number of federal agencies supporting plasma and fusion related activities as part of information gathering to appreciate the funding landscape and access partnering opportunities. Input gained from these activities along with discussions carried out at weekly committee meetings facilitated the development of the LRP report. These activities are described in more detail below.

CPP Process

The CPP, organized under the auspices of the APS Division of Plasma Physics (DPP), was a year-long, community-led process that occurred just prior to our FESAC LRP activity. The findings of the final CPP report were based on the synthesis of community generated white papers, webinars, town halls at major fusion and plasma meetings, and 5 major workshops. The report described opportunities in fusion and plasma science for the purpose of improving our understanding as well as facilitating the translation of science to societally beneficial applications. As such the community report included: 1) Fusion Science and Technology, 2) Discovery Plasma Science, and 3) Cross Cutting Opportunities. The CPP report achieved significant community consensus, and its initiatives and priorities formed the basis for our own prioritization and development of the various budget scenarios.

Committee Focus Groups

In addition to the CPP, the committee gathered additional input through community focus groups. A series of nine focus group sessions were carried out in June–July 2020 with a total of 90 participants. Participants included representatives from all program areas, across demographics and experience levels. The focus group sessions had a number of objectives:

- Address the question of resource division between fusion science and technology and discovery plasma science (called plasma science and technology in this report)
- Determine program synergies and cross cuts
- Gather feedback on the long range planning report formulation process

Virtual Workshop

On August 20 2020, a virtual workshop was held for additional information gathering from the community. The meeting provided an opportunity for the fusion science and technology and plasma science and technology communities to exchange ideas and understand the priorities of each program area. An additional objective of the workshop was to merge the mission and vision statements and values developed in the two communities into a single strategic plan. The effort provided input into development of a process to merge the plans and allocate resources between the two areas in the constrained budget scenarios. The workshop included participation from approximately 200 members of the community.

Stakeholder Federal Agency Briefings

The committee was briefed by representatives from a number of other government agencies and projects with synergistic research interests. The goals of the briefings were to provide insight into plasma related focus areas and their funding footprint in the various agencies, discuss the potential for partnering opportunities, and to learn about the execution of large projects and public-private partnerships by other government agencies. The committee received presentations from the following individuals and agencies:

On synergistic topical reports:
Mike Mauel, on the 2019 NAS report on Burning Plasma Research

Roger Falcone, Felicie Albert, and Jon Zuegel on the NAS report *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*

Mark Kushner and Gary Zank on the 2020 NAS Decadal Assessment of Plasma Science (via attending their presentation to FESAC)

Carolyn Kuranz, Lauren Garrison, Nate Ferraro, Nathan Howard, and John Sarff on the Final CPP Report

From other agencies:
Ann Satsangi, NNSA
Scott Hsu, ARPA-E
Thomas Zurbuchen, NASA
Slava Lukin, NSF

On public/private partnerships:
Alan Lindenmoyer (NASA), on the COTS program
Dave Petti (INL), on the Next Generation Nuclear Plant (NGNP)
Adrian Collins (INL), on the Versatile Test Reactor (VTR)

Committee meetings

As with many other activities in 2020, COVID-19 obviated all plans for the subcommittee to meet in person. The entire subcommittee met weekly via zoom for the duration of our activity, for discussion aimed at understanding overall program needs and synthesizing the overall strategic plan. Additional weekly meetings included separate DPS and FST discussion meetings to develop program-specific priorities, and multiple additional meetings of smaller subgroups tasked with drafting specific portions of the report or addressing issues for later discussion by the larger group. The overarching goal of the meetings was to formulate a plan for three budget scenarios: constant level of effort, modest growth and unconstrained growth (blue sky). Cost estimates for program elements and facilities informed the discussions to develop the three budget scenarios in the FESAC Charge, but were not the sole basis. Status updates were provided at regular (virtual) FESAC meetings on March 16, June 23–24, and August 24.

Costing and Budget Scenarios

DOE Fusion Energy Sciences briefed the committee several times on budgets, providing details of the FY19 budget that is called out in the charge along with historic budget information and information on the FY20 budget enacted. FES also provided information on costs for ITER operations during the 10 year window of the charge. Additional meetings of smaller subgroups took place to establish which program elements and user facilities from the CPP Report would need to be costed by outside experts. Once the list of facilities to be costed was finalized, outside experts were enlisted to provide cost estimates. The list of program elements were costed by the Subcommittee. These cost estimates for the program elements and facilities were used in exercises to understand the three budget scenarios in the FESAC Subcommittee Charge. It was determined by the Subcommittee that the cost estimates of facilities and program elements could only be used to provide a range of plausible costs, given that the facilities were at a low level of development (few were even at the pre-conceptual level). Given the range and the associated uncertainty, the Subcommittee decided not to include cost estimates in the Report and in the budget scenarios. The resulting budget scenarios described in this report are the result of a combination of prioritization within the program as derived from the CPP report and costing exercises targeting the specific budget scenario.

High Heat Flux Facilities

The Community Planning Process (CPP) recognized high-heat flux testing of materials as a critical step in the development of plasma-facing components for future fusion reactors. However, the CPP did not specify how to fulfill this need. Given the safety-driven limitations of international collaborations in the study of nuclear materials (such as the difficulty of transporting activated samples), and the lack of capability for high-repetition, multi-megawatt heat flux exposure currently in the US, we concluded that two new facilities are needed for FPP preparation: a coupon-scale (i.e. sample sizes of cm) high-heat flux exposure facility for candidate material testing and model validation that form the basis for an FPP plasma-facing component designs, both solid and liquid; and a component-scale facility (i.e. sample sizes of tens of cm up to 1m, as needed) for qualification of components and related systems, such as active cooling.

Implementation

This strategic plan and its recommendations are advisory input to FESAC and the DOE-SC office of Fusion Energy Sciences (FES). Implementation of these is the responsibility of FES program management.

Acknowledgements

Finally, the successful completion of this activity and report was enabled by a number of individuals beyond the subcommittee itself. We sincerely thank Jeff Hoy and Carl Strawbridge for their assistance with cost estimation; Jim Dawson for professional editing of the final report and Michael Branigan for layout and graphics; Sam Barish for critical insight from FES throughout the process; and Laurie Moret for facilitating consensus, during both the CPP and LRP activities.

Appendix F: Acronyms

ASCR	Advanced Scientific Computing Research program
AI/ML	Artificial Intelligence/Machine Learning
AFOSR	Air Force Office of Scientific Research
APS DPP	American Physical Society Division of Plasma Physics
ARPA-E	Advanced Research Project Agency-Energy
BCTF	Blanket Component Test Facility
CD	Critical Decision
CPP	Community Planning Process
DEI	Diversity, Equity, and Inclusion
DOD	Department of Defense
DOE	Department of Energy
DPS	Discovery Plasma Science
EPA	Environmental Protection Agency
EXCITE	EXhaust and Confinement Integration Tokamak Experiment
FES	(Office of) Fusion Energy Sciences
FM&T	Fusion Materials and Technology
FPNS	Fusion Prototypical Neutron Source
FPP	Fusion Power Plant
FST	Fusion Science and Technology
GPS	General Plasma Science
HED	High Energy Density
HEP	High Energy Physics
HEDLP	High Energy Density Laboratory Plasma
HEDP	High Energy Density Plasma
HHF	High Heat Flux
ICF	Inertial Confinement Fusion
IFE	Inertial confinement Fusion Energy
INFUSE	Innovation Network for Fusion Energy
ITEP	Integrated Tokamak Exhaust and Performance
LM	Liquid Metal

MEC-U	Matter in Extreme Conditions instrument Upgrade
MPEX	Material Plasma Exposure eXperiment
MFE	Magnetic confinement Fusion Energy
NASA	National Aeronautics and Space Administration
NASEM	National Academy of Science, Engineering, and Medicine
NIF	National Ignition Facility
NIH	National Institutes of Health
NNSA	National Nuclear Security Administration
NSF	National Science Foundation
NTUF	New Tokamak User Facility
ONR	Office of Naval Research
P5	Particle Physics Project Prioritization Panel
PFC	Plasma-Facing Component
PFPO	Pre-Fusion Power Operation
PMI	Plasma-Material Interaction
PPP	Public-Private Partnership
PST	Plasma Science and Technology
QIS	Quantum Information Systems
RF	Radiofrequency
TRL	Technology Readiness Level
USDA	US Department of Agriculture
VNS	Volumetric Neutron Source
WDM	Warm Dense Matter
XFEL	X-ray Free Electron Laser

Powering the Future
Fusion & Plasmas

A long-range plan to deliver fusion energy and to advance plasma science