D R A F T

Fusion Energy Sciences Advisory Committee

Report on

Strategic Planning: Priorities Assessment and Budget Scenarios

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Preface

Fusion, the energy source that powers our sun and the stars, offers the promise of a nearly limitless high-density energy source that does not emit greenhouse gases. Fusion energy could therefore fulfill one of the basic needs of modern civilization: abundant energy with excellent safety features and modest environmental impact that is available to all nations.

The quest for controlled fusion energy— replicating on earth the energy of the Sun— is a noble scientific challenge. After six decades of research, magnetic fusion science has successfully progressed to the threshold of the magnetic fusion energy era. This is an era characterized by burning plasma, steady-state operation, advanced materials that can withstand the harsh environment inside a fusion reactor, and safe regeneration of the fusion fuel from within the reactor.

Throughout its history, the quest for fusion has been a global effort with strong U.S. leadership, especially in terms of diagnostics, experimental research, theory, simulation, and computation. Now the world is engaged in a unique international burning plasma experiment, ITER, to demonstrate the net production of controlled fusion power. ITER is expected to establish the scientific feasibility of magnetic fusion energy and bring this quest to its final hurdle of resolving fusion nuclear science issues associated with demonstration of practical fusion energy.

Simultaneously, international colleagues are building other large-scale facilities with capabilities that complement those in the U.S. Their particular choices in developing these new international facilities provide two opportunities for the U.S. The first is for the U.S. to initiate and grow a new program in fusion nuclear science, including the design of a new world-class facility, an area not being addressed internationally. The second is for the U.S. to selectively engage in international collaborations to access parameter regimes not otherwise available in the U.S. in preparation for the design of this new facility.

This strategic plan has been formulated to enhance and direct areas of U.S. scientific and engineering leadership in coordination with the rapidly expanding international capabilities to realize the prospect of a global fusion energy future at the earliest realistic date. This report provides the basis of that plan with a ten-year vision with priority research recommendations to position the U.S. to make decisive contributions to fusion science in this new era.

The Panel members are indebted to the research community for its thoughtful previous studies and its broad input to this report. The Panel considered this input, leaving no options off the table and resolving conflicts when they occurred, to reach a consensus. The U.S. fusion community looks forward to this transformative era in fusion research, which will lay the foundations for a world-leading subprogram and facility in fusion nuclear science. The challenges would be daunting for a single nation but, with renewed commitment, investment, innovation, and collaboration, a technological advance of immense benefit to the U.S. and to the world will be at hand.

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Executive Summary

The Strategic Planning Panel of the Fusion Energy Sciences Advisory Committee (FESAC) was charged by the Department of Energy's Office of Science to assess priorities within the DOE Fusion Energy Science domestic fusion program for the next 10 fiscal years (2015 through 2024). In answering the Charge, the Panel acknowledges the quality and usefulness of previous FESAC reports and Research Needs Workshops (Appendix H) and the outstanding input of the fusion community.

The Panel concludes that with a bold 10-year strategy the U.S. will continue as a world leader in fusion research. This strategy includes resolving prioritized scientific and technical gaps to allow the pursuit of the most promising scientific opportunities leading to fusion energy development and strengthening international partnerships. The strategy also transitions the U.S. to a fusion energy program bounded by realistic budgets and guided by a "2025 Vision." This vision will enable successful operation of ITER with U.S. participation, provide the scientific basis for a U.S. Fusion Nuclear Science Facility (FNSF), and create a U.S. "Generation ITER-FNSF" workforce that is leading global scientific discoveries and technological innovation.

To realize Vision 2025, the Panel makes four primary recommendations:

- <u>Control of Burning Plasmas</u>: The FES experimental program needs an integrated and prioritized approach to achieve significant participation by the U.S. on ITER. Specifically, new proposed solutions will be applied to two long-standing and ubiquitous issues relevant to tokamak-based burning fusion plasma: dealing with unwanted transients and dealing with the interaction between the plasma boundary and material walls.
- <u>Fusion Predictive Modeling</u>: The FES theory and simulation subprogram should develop the modeling capability to understand, predict, and control both burning, long pulse fusion plasmas, and plasma facing components. Such a capability, when combined with experimental operational experience, will maximize the U.S. operational contribution and the interpretation of ITER results for long pulse, burning plasmas, as well as the design requirements for future fusion facilities. This endeavor must encompass the regions from the plasma core through surrounding materials and requires coupling nonlinear, multi-scale, multi-disciplinary phenomena in experimentally validated, theoretically-based models.
- <u>Fusion Nuclear Science</u>: A fusion nuclear science subprogram should be created to provide the science and technology understanding for informing decisions on the preferred plasma confinement, materials, and tritium fuel-cycle concepts for a Fusion Nuclear Science Facility (FNSF), a proposed U.S.-based international centerpiece beyond 2025. FNSF's mission would be to utilize an experimental plasma platform having a long-duration pulse (up to one million seconds) plasma platform for the complex integration and convergence of fusion plasma science and fusion nuclear science.
- <u>Discovery Plasma Science</u>: FES stewardship of basic plasma research should be accomplished through peer-reviewed university, national laboratory, and industry collaborations. In order to achieve the broadest range of plasma science discoveries, the research should be enhanced through federal agency partnerships that include cost sharing of intermediate, collaborative facilities.

These four recommendations are detailed in Chapters 2 through 5.

The experimental facilities available to implement these recommendations are located in the U.S. and at major international experiment sites. The international experiments provide both access to unique magnetic geometries and extended operating regimes unavailable in the U.S. Those experiments should provide information required to design an FNSF and, ultimately, a fusion demonstration power plant.

The Panel collected information for this report from the U.S. fusion community over five months, including two three-day public meetings. The report will be reviewed by FESAC and then submitted to the DOE's Office of Science. A finalized FES strategic plan will be submitted to Congress by the January 2015 deadline.

As directed in the Charge Letter, the report assumes U.S. participation in ITER, assesses priorities for the U.S. domestic fusion program, and ranks these priorities based on three funding scenarios with the FY14 enacted budget level ($305M) as the baseline, and a fourth cost of living budget scenario based on the FY15 President's budget request ($266M):

- Scenario 1: Modest growth (defined as 2.0% above cost of living)
- Scenario 2: Cost of living
- Scenario 3: Flat funding
- Scenario 4: Cost-of-living (FY15 request)

The Panel worked in four subpanels: (1) Burning Plasma Foundations – the science of prediction and control of burning plasmas ranging from the strongly-driven to the self-heated state; (2) Burning Plasma Long Pulse – the science of fusion plasmas and materials approaching and beyond ITER-relevant heat fluxes, neutron fluences, and pulse lengths; (3) Discovery Plasma Science – the science frontiers of fundamental plasma behavior; and (4) Partnerships with other U.S. and international programs.

The 2009 Magnetic Fusion Energy (MFE) ReNeW Report, a capstone document based on workshops by the fusion community, identified 18 science and technology "Thrusts" defined as needing "concerted research actions." Those Thrusts were considered in this report, along with community input to the Panel in 2014 through presentations, Q&As, and white papers (Appendix E). Closely-related Thrusts were combined, and the prioritization of the Thrusts in metrics based on their importance to Vision 2025 led to the formulation of four overarching Initiatives. These highest-priority Initiatives are:

Tier 1:

- Control of deleterious transient events
- Taming the plasma-material interface

Tier 2:

- Experimentally-validated integrated predictive capabilities
- A fusion nuclear science subprogram and facility

Tier 1 Initiatives are higher priority than Tier 2 Initiatives. Within a tier, the priorities are equal.

In concert with the above Initiatives, Discovery Plasma Science will advance the frontiers of plasma knowledge to ensure continued U.S. leadership.

Descriptions of the Initiatives:

Control deleterious transient events: Undesirable transients in plasmas are ubiquitous but tolerable occurrences in most present tokamak experiments, but some events could prove too limiting to regular operation of an experiment without frequent shutdown for repairs. To reduce the threat of disruptions, both passive and active control techniques, as well as preemptive plasma shut down, will be employed.

Taming the plasma-material interface: The critically important boundary region of a fusion plasma involves the transition from the high-temperature plasma core to the surrounding material. Understanding the specific properties of this boundary region that determine the overall plasma confinement is a priority. At the same time, the properties of this boundary region control the heat and particle fluxes to material surfaces. The response of the material surfaces influences the boundary and core plasma characteristics. Understanding, accommodating, and controlling this complex interaction – including selecting materials to withstand this harsh environment while maintaining high confinement – is a prerequisite for ITER success and designing FNSF.

The Panel concluded that the most cost-effective path to a self-consistent solution to the plasma-materials-interface challenge requires the construction of a prototypic high-power, high-fluence linear divertor simulator. Results from this facility will be iterated with experimental results on suitably equipped domestic and international tokamaks and stellarators, as well as in numerical simulations.

Experimentally validated integrated predictive capabilities: The coming decade provides an opportunity to break ground in integrated predictive understanding that is urgently required as the ITER era begins and plans are developed for the next generation of facilities. Traditionally, plasma theory/computation provides models for isolated phenomena based on mathematical formulations that have restricted validity regimes. However, there are crucial situations where coupling between the validity regime and the phenomena is required, which implies that new phenomena can appear. To understand and predict these situations requires expanded computing capabilities strongly coupled to enhancements in analytic theory and the use of applied mathematics. This effort must be strongly connected to a spectrum of plasma experimental facilities supported by a vigorous diagnostics subprogram in order to provide crucial tests of theory and allow for validation.

Fusion Nuclear Science: Several important near-term decisions will shape the pathway toward practical fusion energy. The selection of the plasma magnetic configuration (an advanced tokamak, spherical torus, or stellarator) and plasma operational regimes needs to be established based on focused domestic and international collaborative long-pulse, high-power research. Another need is the identification of a viable approach to a robust plasma materials interface that provides acceptably high heat flux capability and low net erosion rates without impairing plasma performance or resulting in excessive tritium entrapment. Materials science research needs to be expanded to comprehend and mitigate neutron-irradiation effects, and fundamental fuel-cycle research is needed to identify a feasible tritium generation and power-conversion concept. A new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source is envisioned as a highly cost-effective option.

In concert with the above Initiatives, Discovery Physics Science subprogram elements can provide transformational new ideas for plasma topics. DPS research seeks to address a wide range of fundamental science, including fusion, as outlined by the NRC Plasma 2010 report [Appendix H]. DPS activities are synergistic with the research mission of other federal agencies, and significant opportunities exist to broaden the impact of DPS through the development and expansion of strategic partnerships between FES and other agencies. Addressing fundamental science questions at the frontier of plasma science requires a spectrum of laboratory experimental facilities, from small-scale facilities with a single principal investigator to intermediate-scale highly collaborative facilities. Interactions between larger facilities found at national laboratories and small and intermediate facilities will play an important role in advancing DPS frontiers and in training the next generation of plasma scientists.

The Panel's vision, recommendations, and Initiatives will require redirection of resources over the next ten years. Investments are needed for plasma technology and materials, fusion nuclear science, modeling and simulation, and DIII-D and/or NSTX-U upgrades. Construction of two new facilities – a prototypic high-power and high-fluence linear divertor simulator and an intense, neutron-irradiation source leveraging an existing MW-level neutron spallation source – is recommended. Resources for these investments should derive from a major facility or facilities being closed, mothballed, and/or reduced in "run" weeks, and reconsideration of DPS funding allocations. For all budget scenarios the Panel recommends:

- increased international collaborations, where scientifically justified,
- the operation of at least one major domestic plasma machine,
- the simultaneous operation of DIII-D and NSTX-U for 5 years, and
- the cessation of C-Mod operations.

The Panel recognizes the intellectual leadership and contributions from the MIT Plasma Science and Fusion Center. It is crucial that scientists and engineers from this center take leadership roles in the proposed Initiatives. The five-year operation of NSTX-U enables consideration of a spherical torus magnetic geometry for FNSF. The five-year operation of DIII-D provides optimal investigation of transient mitigation and plasma control for ITER.

Below the Panel summarizes timelines for facilities and Initiatives.

2015 – Initiate cessation of C-Mod operations.

Phase I

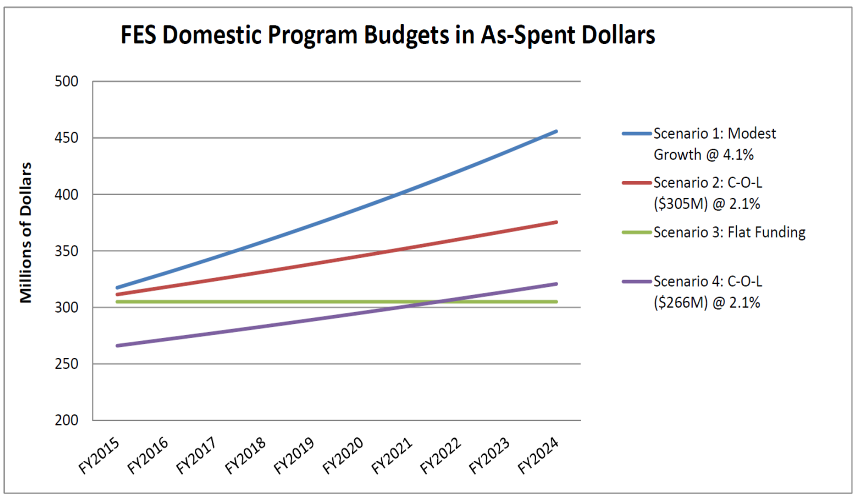
- DIII-D is operating and information on transient mitigation, boundary physics, plasma control, and other ITER-related research is being provided
- NSTX-U is operating and information on a potential path to a FNSR-ST, boundary physics, and ITER-related research is being provided
- Linear divertor simulator is under construction
- Predictive Initiative is launched and grown
- FNS subprogram is initiated
- Scientifically justified international partnerships is increased on leading international superconducting advanced tokamaks and stellarators
- Expanded integration of DPS elements facilitates the effective stewardship of plasma science

Phase II:

- Scientifically justified partnerships centered on current international superconducting advanced tokamaks and stellarators. Minimum of one domestic facility (DIII-D, NSTX-U) operating and providing information for the Interface Initiative

- Linear divertor simulator operating and providing information for Interface Initiative
- Predictive Initiative fully underway and providing information for the Interface Initiative
- FNS Initiative underway and expanding science and technology for fusion materials, including a new neutron-irradiation capability that takes advantage of an existing high-power spallation source
- Priority increasing for fusion power extraction and tritium sustainability
- DPS partnerships advancing the frontiers of DPS knowledge, enhanced by cost sharing on intermediate-scale collaborative facilities

2025 – Vision 2025 achieved depending on budget scenario (see timeline in Chapter 6) with either DIII-D or NSTX-U, operating both for programmatic objectives and as a national user facility for discovery science.



Implementation of the Initiatives is inherently tied to the four budget scenario assumptions (FY2015 – FY2024). The funding is bound on the high end by Budget Scenario 1 ($305M with modest growth of 4.1% per year) and on the low end by Budget Scenario 4 (FY2015 President's Budget Request of $266M with cost of living increase of 2.1% per year). As an example of the variation for these two funding models, Budget Scenario 4 starts out with $52M less than Budget Scenario 1 in FY2015 and ends up with $135M per year less in FY2024. From FY2015 through FY2024, the total integrated amount differs by approximately $900M between the low- and high-end budget scenarios.

The Panel explored a variety of funding scenarios for the ReNeW Thrusts in order to derive credible funding profiles for the highest priority research activities. The Panel projects the following probable consequences:

- Scenario 1 – 2014 Modest Growth – Modest growth of appropriated FY2014 ($305M) at 4.1%. This has the highest integrated funding. Vision 2025 has an acceptable probability of being achieved. Both NSTX-U and DIII-D facilities operate for 5 years and possibly for 10 years (at reduced availability), with one upgraded divertor. If funding only one of the facilities is possible, it is not yet clear which is optimal. After 10 years only one facility is required, but it is not clear which one. All four Initiatives go forward, informing the design of FNSF. Both the divertor simulator and neutron-irradiation capability are providing data. The U.S. Fusion Program features prominently in four areas: Transients, Interfaces, Predictions, and importantly, FNS.

- Scenario 2 – 2014 Cost of Living – This has the second highest integrated funding, but at the end of FY2024 these integrated funds are approximately $400M less than in Budget Scenario 1. There is a lower probability that Vision 2025 can be met. One of the two remaining major tokamak facilities, DIII-D and NSTX-U, will be closed or mothballed between 2020 and 2025, and DPS funds may be affected. Only one major tokamak facility is required beyond 2025. All four Initiatives go forward, with three (Transients, Interface, Predictions) being emphasized. If necessary the Tier 2 Initiative FNS is slowed down. The U.S. Fusion Program features prominently in at least three Initiative areas: Transients, Interfaces, Predictions, with the possibility of featuring prominently in the FNS Initiative.

- Scenario 3 – 2014 Flat – This has the third highest integrated funding, but at the end of FY2024 these integrated funds are approximately $780M less than the highest budget, Budget Scenario 1. Vision 2025 will be only partially met. One of the two remaining facilities, DIII-D and NSTX-U, will be closed or mothballed between 2020 and 2025, earlier than in the Budget Scenario 2, and DPS funds affected. Only one major tokamak facility will remain beyond 2025. The divertor simulator is scientifically productive. The two Tier 1 Initiatives (Transients, Interfaces) and one Tier 2 Initiative (Predictions) go forward, but the Tier 2 Initiative FNS is slowed. The U.S. Fusion Program features prominently in two, or possibly three, Initiative areas: Transients, Interfaces, and Predictions.

- Scenario 4 -- 2015 Cost of Living – Integrated funding over the 10-year period is about $900M less than Budget Scenario 1. Vision 2025 will be partially met, but a second Initiative is lost. However, the U.S. will maintain leadership in the research field encompassed by the two Tier-1 Initiatives, specifically Transients and Interfaces. The necessary delay to the Initiatives FNS and Predictive could allow international partners to take the leading role in these areas. The U.S. could feature prominently in two Initiative areas: Transients and Interfaces.

Focused effort on the four proposed highest-priority Initiatives, together with existing strengths in diagnostics, experimental research, theory, simulation, and computation, will promulgate a vibrant U.S. fusion energy sciences program that can lead in emerging fusion nuclear science research.

Chapter 1. Introduction and Background

Fusion Science -- A Forward Look

Harnessing fusion energy offers enormous potential for improving the global quality of life by providing an abundant, inherently safe, and environmentally benign supply of energy. Seven governmental agencies representing more than half of the world's population (China, the European Union, India, Korea, Japan, Russia, and the U.S.) have united in an unprecedented collaboration to build ITER, a magnetic confinement fusion reactor experiment that is expected to be a major step forward in the quest for commercial fusion energy. Scientists anticipate that ITER, under construction in St. Paul-lez-Durance, France, will produce 500 megawatts of fusion thermal power, demonstrating the feasibility of large-scale fusion energy.

In addition to collaborating on ITER, the U.S. collaborates on other international fusion projects and utilizes mature domestic fusion facilities with well-diagnosed experiments. The overall U.S. fusion program is categorized into three "Burning Plasma" thematic areas that focus on conditions relevant to: Burning Plasma High Power (not considered here); Foundations; and Long Pulse. There is an important fourth component that is separate from the burning plasma thematic areas: Discovery Plasma Science. Although U.S. facilities undergo routine upgrades, international collaborators have made more significant investments in their domestic fusion confinement programs and, as a result, are developing experimental capabilities that soon will far exceed those in the U.S.

The investment choices that international colleagues have made in developing these new international facilities and the fact that the U.S. is currently not committed to major fusion investment, provide two opportunities for the domestic fusion program. First, the international investments in fusion do not include a Fusion Nuclear Science Facility (FNSF) that is critical as a bridge between ITER and an eventual demonstration reactor. Fusion science requires that this facility be developed, and if the U.S. seizes this opportunity to create an FNSF, it will be the world leader in this area. Second, the developing international capabilities provide opportunities for the U.S. to pursue its objectives in more relevant fusion conditions, including those required to inform a design of an FNSF. Taking advantage of these two opportunities, together with our existing strengths in diagnostics, experimental research, theory, simulation, and computation, would result in a vibrant U.S. fusion energy program that has a new focus and unique world leadership.

The U.S. supports highly visible and productive research programs in the area of fundamental discovery plasma science and engineering. Knowledge generated by these subprograms advances our understanding of natural phenomena such as space weather, solar dynamics, and supernova explosions. The discoveries are often used in technological devices – ranging from etching and deposition of materials in microelectronics fabrication to surgical instruments – that benefit everyday life. Fundamental plasma science research has laid the groundwork for the magnetic fusion plasma science effort that has brought us to the brink of the fusion energy era. Stewardship of this vital research subprogram will result in continued fundamental science discovery and application innovation.

Discussion of the Charge Letter and Approach Taken By SP Panel

In April 2014, FESAC was given a Charge by DOE to assess the priorities among continuing and new scientific, engineering, and technical research subprogram investments within and between each of three FES subprograms:

1. The science of prediction and control of burning plasma ranging from the strongly-driven state to the self-heated state. This subprogram is labeled *Burning Plasma Science: Foundations* (referred to in this report as **Foundations)**.

2. The science of fusion plasmas, plasma-material interactions, engineering and materials physics modeling and experimental validation, and fusion nuclear science approaching and beyond ITER-relevant heat fluxes, neutron fluences, and pulse lengths. This subprogram is labeled *Burning Plasma Science: Long Pulse* (referred to as **Long Pulse)**.

3. The study of laboratory plasmas and the high-energy-density state relevant to astrophysical phenomena, the development of advanced measurement validation, and the science of plasma control important to industrial applications. This subprogram is labeled *Discovery Plasma Science (referred to as* **DPS)**.

In order for FES to provide Congress with a Strategic Plan by January 2015 as requested in the Fiscal Year 2014 Omnibus Appropriations Act, the DOE-SC asked FESAC:

- to prioritize the FES defined subprograms,
- to include FESAC views on new facilities, new research initiatives, and facility closures,
- to establish a scientific basis for advancing fusion nuclear science, and
- to assess the potential for strengthened or new partnerships with other federal agencies and international research programs that foster opportunities otherwise unavailable to U.S. fusion scientists.

A 19-member FESAC Strategic Planning Panel, consisting of FESAC members and outside experts, was convened in May 2014 to respond to the Charge in a report that the Panel presented during the FESAC September 22-23, 2014 meeting.

Although the Panel was aware of the subprogram elements of the fusion program described and prioritized by previous FESAC reports, the Panel understood the need for additional U.S. fusion community input as a basis for a report that would address the Charge's specific budget scenarios for advancing FES subprograms. Community input on initiatives for FES for the next ten years relevant to Foundations, Long Pulse, and DPS were presented during two public meetings (June 3-5 and July 8-10, 2014). The U.S. and international fusion communities were encouraged to submit white papers that were posted for public viewing on the Panel website found at https://www.burningplasma.org/activities/ or https://www.burningplasma.org/activities/?article=2014%20FESAC%20Strategic%20Planning%20Panel

The Panel was organized into four subpanels, three representing the three FES subprograms (Foundations, Long Pulse, DPS), and one representing leverage and partnership opportunities with other federal programs and international programs. These subpanels considered key FESAC and community reports, in particular, the "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy (2007); Research Needs for Magnetic Fusion Energy Sciences (2009); Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program (2013); Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program (2013); Opportunities for and Modes of International Collaboration in

Fusion Energy Sciences Research during the ITER Era (2012); Opportunities for Fusion Materials Science and Technology Research Now and During the ITER Era (2012); Low Temperature Plasma Science Workshop (2008); Plasma Science: Advancing Knowledge in the National Interest (2007); Basic Research Needs for High Energy Density Laboratory Physics (2010); Workshop on Opportunities in Plasma Astrophysics (2010); and Prioritization of Proposed Scientific User Facilities in the Office of Science report (2013) [Appendix H], as well as the community input discussed above.

The Panel established a 10-year approach based on Vision 2025 that would:

a. Enable successful operation of ITER with significant U.S. participation and leadership
b. Provide the scientific basis for a U.S. Fusion Nuclear Science Facility (FNSF)
c. Create a U.S. "Generation ITER-FNSF" workforce that leads scientific discoveries and technological innovation.

Each subpanel identified candidate initiatives, primary and supporting recommendations, and minimum funding requirements to meet Vision 2025. The Panel integrated and iterated these findings (see Appendix A), resulting in four high priority Initiatives that could be accommodated over ten years under a majority of the budget scenarios. These Initiatives were further ranked into upper and lower tiers, with an understanding that those in the lower tier would be delayed under the lower budget scenarios.

Initiatives and Recommendations

In Chapters 2 and 3, the Thrusts relevant to Foundations and Long Pulse will be individually discussed. In those sections the eighteen science and technology Thrusts from the 2009 ReNeW Report are considered, along with valuable community input to the Panel in 2014 through presentations, question and answer sessions, and white papers (*cf.* Appendix X). Closely related Thrusts that addressed an overarching topic were combined into an overarching Initiative. Prioritization of the Thrusts in terms of metrics that included their importance to Vision 2025 directly led to formulation of four overarching Initiatives. The four highest priority Initiatives, categorized in two tiers, are:

Tier 1:

- Control of deleterious transient events (Transients)
- Taming the plasma-material interface (Interface)

Tier 2:

- Experimentally Validated Integrated Predictive Capabilities (Predictive)
- Fusion nuclear science (FNS)

Tier 1 Initiatives are higher priority than Tier 2 Initiatives. Within a tier, the priorities are equal.

In concert with the above Initiatives, Discovery Plasma Science will advance the frontiers of plasma knowledge to ensure continued U.S. leadership.

Descriptions of the Initiatives are:

<u>Control deleterious transient events</u>: Undesirable transients in plasmas are ubiquitous but tolerable occurrences in most present tokamak experiments, but some

events could prove too limiting to regular operation of an experiment without frequent shutdown for repairs. To reduce the threat of disruptions the Panel recommends a robust multi-level strategy evolving from present experiments and improving predictive modeling.

Taming the plasma-material interface: The critically important boundary region of a fusion reactor includes the transition from the high-temperature, confined plasma core to the low-temperature material structure that surrounds the plasma. The fusion power generated in the core plasma is directly impacted by the structure and behavior of the boundary region. Steep plasma-pressure profiles having large gradients at the edge of the core plasma (termed the H-mode pedestal) are essential to support a sustained high-pressure (and therefore high-fusion-power) core plasma. Understanding the processes that allow these large gradients to form and affect plasma stability is a priority. Heat and particle exhaust from the high-power fusion-power core flows through the pedestal region into a thin layer termed the scrape-off layer (SOL) that surrounds the core plasma. This exhaust is conducted through this thin layer to material structures surrounding the plasma. The properties of the thin surrounding layer (its width in particular) ultimately determine the intensity of the heat and particle fluxes that become established. The engineering solution for these material structures is strongly constrained by this intensity.

Understanding the physics of the thin surrounding layer and seeking solutions to control how this flux impinges on material surfaces is therefore a high priority. Materials must be engineered to withstand this harsh environment.

Experimentally validated integrated predictive capabilities: The coming decade provides an opportunity to break ground in the integrated predictive understanding that is required as the ITER era begins and plans are developed for the next generation of facilities. Traditionally, plasma theory and simulation provide models for isolated phenomena based on mathematical formulations that are only strictly valid over a limited region of the plasma or restricted to particular spatial and temporal scales. Hence, DOE has historically organized its funded theory and simulation enterprises by topical element (e.g., radio-frequency heating, extended MHD, turbulent transport, etc.). While gaps remain in these elements, the U.S. theory and simulation subprogram has provided many contributions to improved predictive understanding and has spearheaded validation efforts on a variety of experimental configurations. However, there are crucial areas of fusion science for which coupling of topical elements is required to further understand and attain predictive capability. Examples include active control/mitigation modeling of deleterious MHD instabilities, core-edge coupling, plasma-surface interaction, 3D-field effects on edge/pedestal properties, etc. The strong coupling of physics phenomena implies that new phenomena mechanisms can appear that cannot generally be predicted with theory tools that rely on single-component phenomenon models. This kind of transformational change in our understanding of the overall behavior, physics, and processes is critical if we are to aim for true predictive modeling. These advances can be made with expanded computing capabilities strongly coupled to enhancements in analytic theory and applied mathematics understanding. This effort must be strongly connected to a spectrum of plasma experimental facilities supported by a vigorous diagnostics subprogram in order to provide a platform for validating theory with experiment.

A fusion nuclear science subprogram and facility: Several near-term decisions that will shape the pathway toward practical fusion energy. The selection of the plasma configuration (AT vs. ST, tokamak vs. stellarator) and plasma operational regimes need to be established on the basis of focused domestic and international collaborative long-pulse, high-power research. There is also a need for the identification of a viable approach to a robust plasma materials interface that tolerates acceptably high heat flux capability and provides low net erosion rates without impairing plasma performance or tritium entrapment. Materials science research must be expanded to comprehend intense fusion neutron-irradiation effects on property degradation of structural materials and to design potential materials science approaches to mitigate these degradation phenomena. A new fusion materials neutron-irradiation facility that takes advantage of an existing magawatt-level neutron spallation source is envisioned as a cost-effective option. Fundamental research is needed to identify a feasible tritium fuel-cycle and power-conversion concept, including improved understanding of the permeation and trapping of tritium inside candidate coolants and fusion materials, exploration of viable methods for efficiently extracting tritium from hot flowing media, and improved understanding of complex magneto-hydrodynamic (MHD) effects on the flow of electrically conductive coolants in confined channels. Acquisition of new knowledge in all of these fusion nuclear science research areas is needed in order to provide the scientific basis for the conceptual design of a Fusion Nuclear Science Facility.

In concert with the above Initiatives, effective DPS subprogram elements can provide transformational ideas for plasma topics. DPS research addresses a wide range of fundamental science, including fusion, as outlined by the NRC Plasma 2010 report. DPS activities are synergistic with the research mission of other federal agencies, and opportunities exist to broaden the impact of DPS through the expansion of strategic partnerships between FES and other agencies. Addressing fundamental science questions at the frontier of plasma science requires a spectrum of laboratory experimental facilities from small-scale facilities led by a single investigator to intermediate-scale, highly collaborative facilities. The development of intermediate-scale and multi-investigator facilities would be prioritized to address a wider range of scientific questions with comprehensive diagnostic suites. Mutual interactions between larger facilities found at national laboratories and smaller facilities will play an important role in advancing DPS frontiers and in training the next generation of plasma scientists. These Initiatives, together with the findings of the DPS subpanel, are transposed into four primary recommendations listed in the Executive Summary.

Chapter 2: Burning Plasma Physics: Foundations

Definition and status

The subprogram Foundations encompasses fundamental and applied research pertaining to the magnetic confinement of plasmas with emphasis on ITER and future burning plasmas. Both experimental and theoretical contributions are included in Foundations with the key objectives being to establish the scientific basis for the optimization of approaches to magnetic confinement fusion based on the tokamak (including the spherical torus), develop a predictive understanding of burning plasma behavior, and develop technologies that will enhance the performance of both existing and next-step machines.

The existing elements of the subprogram are:

a) The research and operations of three major U.S. machines, the DIII-D tokamak located at General Atomics, the National Spherical Torus Experiment Upgrade (NSTX-U) at Princeton Plasma Physics Laboratory (PPPL), and the C-MOD tokamak at the Massachusetts Institute of Technology (MIT). Infrastructure improvements to these

facilities are included, but activities pertaining to steady-state operation and fusion nuclear science are part of the Long Pulse category.
b) Theory and Scientific Discovery Through Advanced Computing (SciDAC) activities.
c) Smaller tokamak projects.
d) Heating, fueling and transient mitigation research.

The DIII-D research goal is to establish the scientific basis for the optimization of the tokamak approach (Advanced Tokamak) to magnetic confinement. DIII-D research activities also address near-term scientific issues critical to the successful construction of ITER, including tests of the feasibility of disruption mitigation and ELM reduction on ITER and developing the scientific basis for both the standard operating scenario to achieve high-gain fusion and the more advanced long-pulse operating scenario. These issues are also pertinent to the mission of a future FNFS. Present activities also include experimental validation of transport theoretical models and testing the simultaneous achievement of high-performance core plasmas with fusion-relevant edge scenarios.

The primary mission of the NSTX-U subprogram element is to evaluate the potential of the low-aspect ratio tokamak, or spherical torus, to achieve the sustained high performance required for a Fusion Nuclear Science Facility. ITER-relevant research on NSTX-U includes energetic particle behavior and high-beta disruption control. Innovative plasma-material-interface (PMI) solutions are another important element of this program. The ITER-relevant research will also address energetic particle behavior and high-β disruption control.

The C-Mod research mission is to help establish the plasma physics and engineering requirements for a burning plasma tokamak experiment, with FY 2015 research focusing on experiments that address issues of ITER-relevant boundary and divertor physics, as well as disruption studies.

Theory and simulation research advances the scientific understanding of fundamental physical processes governing the behavior of magnetically confined plasmas and develops predictive capability by exploiting leadership-class computing resources.

Smaller tokamak projects center on innovative niche issues of the AT and ST configurations. These projects include the spherical torus LTX at the Princeton Plasma Physics Lab to study liquid-metal PFC solutions, Pegasus at the University of Wisconsin with the mission to study non-solenoidal startup and edge stability, and the HBT-EP tokamak at Columbia University to develop MHD mode control in high-β plasmas.

Thrusts

The ReNeW report surveyed the range of scientific and technological research frontiers of fusion science and identified eighteen Thrusts determined by specific research needs. Many of the Thrusts are interrelated, some in ways not fully understood at the present time. Most must be addressed to move to a program in fusion energy. The subset of the Thrusts that have been selected in this report as the highest priorities are evaluated according to the metrics described in Ch. 1. The research drivers for the Thrusts are:

Thrust 1: Develop measurement techniques to understand and control burning plasmas
Thrust 2: Control transient events in burning plasmas
Thrust 3: Understand the role of alpha particles in burning plasmas

Thrust 4: Qualify operational scenarios and the supporting physics basis for ITER
Thrust 5: Expand the limits for controlling and sustaining fusion plasmas
Thrust 6: Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement
Thrust 7: Exploit high-temperature superconductors and other magnet innovations
Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas
Thrust 9: Unfold the physics of boundary layer plasmas
Thrust 10: Decode and advance the science and technology of plasma-surface interactions
Thrust 11: Improve power handling through engineering innovation
Thrust 12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma
Thrust 13: Establish the science and technology for fusion power extraction and tritium sustainability
Thrust 14: Develop the material science and technology needed to harness fusion power
Thrust 15: Create integrated designs and models for attractive fusion power systems
Thrust 16: Develop the spherical torus to advance fusion nuclear science
Thrust 17: Optimize steady-state, disruption-free toroidal confinement using 3-D magnetic shaping
Thrust 18: Achieve high-performance toroidal confinement using minimal externally applied magnetic field

According to the Charge's guideline to separate research issues into the categories provided by FES, eight of these Thrusts (1-6, 9, and 16) pertain to the category of Foundations and are relevant for this chapter, which focuses on fusion science carried out in tokamaks and spherical tokamaks. Most of the remaining Thrusts (7, 10-15, and 17) are discussed in the next chapter on Long Pulse, and Thrust 18 is discussed in Ch. 4 on DPS. Several Thrusts overlap with each other and are important across FES subprograms.

Priorities

The Panel concludes that three subprogram elements within Foundations should have high priority over the next ten years. The Transients Initiative and the Interface Initiative have the highest priority and the Predictive Initiative has the next highest priority.

Avoiding the consequences of deleterious transients is essential in a fusion power plant. The two primary concerns for large tokamaks, including ITER, are disruptions and edge-localized modes. While they are tolerable phenomena in present tokamak experiments, they are forecast to be too destructive to be withstood in a facility of the scale of ITER or DEMO, the demonstration fusion plant that would build upon the experimental success of ITER. Disruptions can have the following consequences:

- Enhanced energy flux to the divertor and wall
- Large electromagnetic loads on the vacuum vessel due to halo currents
- Localized energy/particle flux due to runaway electrons

While ELMs have the beneficial effect of reducing the influx of impurities to the core of the plasma, they can, under common circumstances, deliver large transient heat fluxes to the divertor. In plasmas of the scale of ITER, FNSF, and DEMO, the impulsive heat flux is predicted to exceed the safe thermal power thresholds of the plasma-facing material in the divertor unless it is mitigated.

The urgency of this Transients Thrust is driven by the necessity to operate ITER with as few disruptive events as possible in order to meet the facility's objective of sustained fusion power production. Demonstrated control of disruptions is considered even more important for either an advanced or spherical tokamak as the confinement configuration of an FNSF. Mitigation of disruptions is becoming a standard protective technique in large tokamaks, and the U.S. is responsible for providing the appropriate hardware for ITER. Furthermore, several successful techniques for reducing the pulsed heat loads from ELMs are under investigation around the world. U.S. scientists are in the forefront of all of these research areas.

Developing boundary solutions (Interface Initiative) is the other priority in Foundations. The boundary region of a fusion reactor comprises the transition from the high-temperature, magnetically confined plasma core to the lower-temperature material that surrounds the plasma. Heat and particle exhaust from the hot plasma core flows through the magnetic separatrix into the thin scrape-off-layer (SOL) surrounding the plasma in which the magnetic field lines terminate on the material surroundings. Magnetic divertors near the wall disperse the exhausted power over a broad area and neutral gas in the divertor and SOL can convert much of the incident heat flux to radiation, which also serves to disperse the exhaust heat over a large surface area.

Understanding the phenomena taking place within the boundary region is important because the density and temperature of the core plasma (and hence the fusion power generated in a burning plasma) is remarkably dependent on the behavior of the boundary region. A steep plasma-pressure profile having a large gradient at the edge of the core plasma constitutes a local barrier (reduction) to the transport of heat and particles into the scrape-off layer. This barrier is essential to maintaining a sufficiently high temperature core plasma in the burning plasma regime. The edge-localized modes, mentioned above, periodically collapse this pedestal. Understanding the processes that allow this pedestal to form, regulate its magnitude, and impact its stability is critical.

The magnetic geometry of the scrape-off layer and the plasma and atomic processes taking place within it ultimately determine the intensity of the heat and particle fluxes to the walls and divertor. The engineering solution for these material structures is strongly constrained by this magnitude of the intensity of the fluxes that get established. Materials must be engineered to withstand this harsh environment; challenges include potentially unacceptable material erosion and redeposition from intense particle fluxes, excessive tritium entrainment in redeposited layers, and high heat flux melting of plasma facing armor and associated thermal fatigue damage to underlying structures. Recent scaling studies from a variety of tokamaks indicate that the heat flux to the ITER divertor is predicted to be several times higher than the previously accepted values. Theory and simulation applied to the edge region to provide predictive understanding for ITER and beyond is not as developed as for other plasma phenomena. Understanding the physics of the scrape-off layer and developing solutions that control how this flux impinges on material surfaces is a high priority. Several potential approaches for mitigating some of these plasma-materials interface effects have been proposed but need to be explored theoretically and on appropriate linear plasma-materials-interface facilities and tokamaks.

In summary, edge plasma physics is an area in which the level of technical readiness needs to be raised to prepare for ITER research and the development of FNSF.

Integrated predictive capability (Predictive Initiative) is the next priority in the Foundations area. The essence of scientific understanding is the development of predictive models based on foundational theory that is validated against experimental measurements. This Thrust combines analytic theory, computational modeling, and experimental validation to establish predictive capability that links the science of different regions in the plasma and topical areas of plasma physics. This capability is necessary for reliable extrapolation to the operating regimes that will occur in ITER and successor devices. It is also essential to minimize risk in the design of FNSF. The combination of increasing computational power and the cost of future experiments makes this Thrust extremely timely.

At present, the U.S. is the leader in theory and simulation in several areas of fusion energy science. That success is mostly due to the close coordination with the experimental facilities that allow examination of a broad range of plasma parameters and focus.

In a number of topical areas, relatively mature development in the U.S. theory and simulation subprogram element exists. These areas include core transport, extended magnetohydrodynamics, energetic particles, radio-frequency heating, and 3D-field effects, with support provided by both base theory and SCIDAC programs that target individual topical areas. However, there are other areas in which substantial development is required. These areas include pedestal physics, scrape-off-layer/divertor, plasma-surface interaction, and material science. While gaps remain in these areas, the U.S. theory and simulation subprogram has provided many contributions that successfully predict experimental phenomena.

Initiatives

1. Controlling transient events in burning plasmas

The major domestic experimental subprogram elements will focus on U.S. scientists playing influential roles on ITER. As part of this strategy, the U.S. program will sustain its attack on controlling edge localized modes and disruptions. The Panel believes that the favorable and timely resolution of these challenges benefits from a distinct strategic Thrust that is coupled with the broader elements of boundary physics and integrated predictive capability. Although there have been notable advances over the years of experience with tokamaks, there is still a need to gain a deeper scientific understanding of the transient events and of the actuators proposed to control them under a variety of plasma conditions relevant to burning plasmas. The Transients Initiative seeks to reduce the effects of ELMs and disruptions in ITER and simultaneously develop more reliable predictive models to employ in the design of future burning plasma experiments in which the plasma is less tolerant to transient events, the control actuators less accessible, and the consequences to reliable operation more severe.

Strategic international partnerships are required over the next decade to investigate key scientific issues, specifically collaborations that exploit the unique capabilities of superconducting long pulse tokamaks such as EAST, KSTAR, the JET-sized superconducting tokamak JT-60SA, which will start operation in 2019, and stellarators including LHD and W7-X.

ELMs commonly occur in the pedestal region near the boundary of high-performance tokamak plasmas. Several promising techniques for mitigating the pulsed heat loads from ELMs have been developed from U.S.-led efforts. That knowledge is critical as the U.S. has prime responsibility for implementing such mitigation methods on ITER. Because of this responsibility, the U.S. program should emphasize the Transients Initiative to actively modify the edge plasma conditions to mitigate large ELMs using a variety of techniques, including applied 3D magnetic-field perturbations and timed injection of pellets into the edge plasma. It should further explore plasma regimes that are suitable for burning plasma scenarios in which deleterious ELMs do not arise.

To negate the consequences of disruptions in large tokamak plasmas beyond simple avoidance of unstable operating conditions, U.S. researchers will employ a multi-level strategy informed by ongoing experiments and improved theoretical understanding. Actuators and associated diagnostic tools employing state-of-the art control theory will maintain passive stability by steering plasmas away from disruptive states, actively stabilize disruptive precursors when they arise, and pre-emptively shut down the plasma as a last resort to avoid the worst consequences of disruptions.

Continued development of the stellarator, in which tokamak-like disruptions do not occur, will also be pursued. The U.S. should maintain its collaborations with the large foreign stellarators as its primary means of engaging in stellarator-centered fusion science, and on W7-X in particular, where a collaborative agreement already exists.

Experiments conducted on international facilities that have the requisite diagnostic capability will provide the necessary data for model validation. Collaborations with international theorists through individual exchanges and through formal projects (such as verification exercises coordinated by the International Tokamak Physics Activity) will spur development of key computer simulation modules. Ultimately, a mature predictive model can provide advance information needed to safely plan experiments on large international devices.

Research plan for Transients Initiative:

The U.S. program will conduct research on domestic facilities to further improve the prediction and avoidance of major disruptions in tokamaks, and to reduce the potential for divertor and first-wall damage to tolerable levels through robust mitigation. Similar research will be maintained to improve the suppression of ELMs.

Initially, the experimental research should be carried out using the short-pulse, well diagnosed DIII-D and NSTX-U devices. Because of the rapid growth rates of transient events, they can best be investigated on existing facilities. The Panel envisions the work to take place primarily on DIII-D, which already conducts active research in both disruptions and ELMs and is well suited for this work. An upgrade of the hardware for the 3D magnetic-field perturbation coils is recommended.

The research could be transitioned to the longer pulse EAST in China and KSTAR in South Korea, which are devices that have fully stationary current and pressure profiles, but this should be staged late in the 10-year period. Research teams from EAST and KSTAR could be included in collaborative research activity to facilitate this subsequent transition. The most important transition for this research will be operating ITER Baseline and subsequently Advanced Tokamak discharges in ITER with minimal transient events, but this will occur beyond the 10-year horizon of this plan.

- Recommendation: *Maintain the strong experimental U.S. focus on eliminating and/or mitigating destructive transient events to enable the high-performance operation of ITER. Develop improved predictive modeling of plasma behavior during controlled* *transient events to explore the basis for the disruption-free sustained tokamak scenario for FNSF and DEMO.*

2. Taming the plasma-material interface

The primary goal of the Interface Initiative is to develop the physics understanding and engineering solutions for the boundary plasma and plasma-facing components that will enable the operation of a high-power fusion core with acceptable material lifetimes.

Research plan for Interface Initiative:

a. Pedestal structure: Develop first-principles understanding and predictive capability for the structure of the edge pedestal, in particular the pedestal height.
b. SOL structure: Understand the physics of the heat flux width, including a predictive capability for the heat flux incident on divertor materials and other in-vessel components such as RF antennas.
c. Explore solutions to mitigate heat flux such as advanced divertor solutions.
d. Evaluate impact of PMI on boundary and core performance.

This Initiative will engage improved theoretical modeling with experiments conducted on toroidal confinement facilities with a research focus on the boundary, scrape-off layer, and divertor (both tokamak and stellarator experiments are expected to contribute). The Panel advocates that one major U.S. facility be made available as part of this Initiative for innovative boundary studies with advanced divertor scenarios as an upgrade during the latter half of the 10-year period. This effort will use the fundamental studies of plasma-materials interaction in the Long Pulse subprogram and will transition to steady-state boundary research on long-pulse international superconducting tokamaks, also in the Long Pulse subprogram.

- Recommendation: *Undertake a technical assessment with community experts to ascertain which existing facility could most effectively address the key boundary physics issues.*

3. Experimentally Validated Integrated Predictive Capabilities

Crucial areas of fusion science require coupling of topical subprogram elements to understand and attain predictive capability. Examples include active control and mitigation of disruption events, core-edge coupling, plasma-surface interaction, and 3D-field effects on edge and pedestal properties. The strong coupling of physics implies that new phenomena can appear that cannot generally be predicted with theory tools that rely on single-phenomenon models. This kind of transformational change in the understanding of the overall behavior, physics, and processes is critical in order to achieve true integrated predictive modeling.

Research plan for Predictive Initiative

The new Initiative in integrated predictive capability should start with the binary integration of single-topic elements in which both of the individual elements are well developed and integration is required to expand predictive capability to address research priorities. The Panel envisions projects by teams that include analytical theorists, computational plasma physicists, computer scientists, applied mathematicians, and experimentalists. In order to proceed to integrated, predictive understanding, continued development in the existing topical areas is required. The success of this integration activity is contingent upon the validation of the individual-element components. The need for continued development is particularly important to topical areas with lower maturity level. Additionally, theory and simulation efforts should be expanded in support of the previously articulated Transients and Interface Initiatives.

As coupling of computational elements leads to new technical issues not present in single-element enterprises, the plasma theory and simulation program should seek assistance from the broader computational science and applied mathematics communities. High quality simulation capabilities require researchers who have experience interacting between the areas of experimental operation, theoretical modeling, numerical discretization, software engineering, and computing hardware.

A robust analytic theory subprogram element is essential to the success of the computational science effort. Analytic theory has played a decisive and foundational role in the development of fusion plasma physics by providing rigorous foundations for plasma modeling, elucidating fundamental processes in plasmas, and providing frameworks for interpreting results from both experimental results and simulation results. Increased analytic understanding is needed to achieve integrated predictive capability in comprehensive modeling.

With a long-term vision of the complete integration of all topical areas, it is recommended that community-wide planning should be initiated for the eventual integration of program elements. Additionally, there is a need to identify areas where substantial advances can be made with increased computational power. The introduction of exascale computing enables well-resolved simulations for single-topic computational tools and allows for the possibility of integrated predictive understanding through code coupling.

The Predictive Initiative must be closely connected to a spectrum of plasma experimental facilities supported by a vigorous diagnostics subprogram in order to provide crucial tests of theory and provide a platform for validation.

- Recommendation*: Maintain and strengthen existing base theory and SCIDAC subprograms to maintain world leadership and leverage activities with the broader applied mathematics and computer science communities.*

- Recommendation: *Ensure excellence in the experimentally validated integrated Predictive Initiative with a peer-reviewed, competitive proposal process. A community-wide process is needed to define the scope and implementation strategy for realizing a whole-device predictive model.*

4. Contributions to FNS Initiative and to the elements of Vision 2025

While not called out as high priorities within the three Initiatives described above, a number of the other Thrusts are important in their contribution to U.S. engagement in ITER, the definition of a science facility for the emerging fusion nuclear science program, and to the Thrusts that motivate the selected Initiatives. The development of new plasma diagnostics is cross cutting and crucial to all of the Initiatives. Successful completion of the Predictive Initiative, will require new diagnostics that target key validation efforts. For Long Pulse, new diagnostics that can function in the harsh reactor environment will be needed in ITER and beyond. For DPS, innovative diagnostics techniques can unlock new areas of discovery.

The success of ITER is best ensured by the strategic progress outlined in the 10-year plan. Specifically, the Predictive Initiative will benefit from linking work on operating scenarios and the observations associated with control techniques. Fusion-product effects (Thrust 3) and the self-consistent interplay between alpha-particle heating and the thermal plasma (Thrust 8) are major, novel elements emphasized in ITER's research program. Understanding these effects is necessary for a successful FNSF. Within this strategic plan, ongoing research in the FNS Initative is an important contributor to the Predictive Initiative. Using its domestic facilities, the U.S. has the opportunity to develop operating scenarios for ITER (Thrust 4). These activities prepare U.S. researchers for active participation in ITER's baseline operation.

Advancing the tokamak concept to true steady-state capability motivates the development of effective strategies and actuators for controlling the plasma, specifically its current and its stable radial current profile for as long as required, on short time scales on which discharge-terminating instabilities must be suppressed and on longer time scales for maintaining the plasma equilibrium. (Thrust 5). Achieving the former is captured to some extent in the Transients Initiative. The latter aspect emphasizes achieving adequate control and sustainment of the steady-state plasma equilibrium, which is a prerequisite for tokamak scenarios of FNSF and will also be explored in extended-pulse experiments on ITER.

The FNS Initiative to pursue the FNSF as an aspect of a broader fusion nuclear science subprogram is described in the next chapter. Much of the long pulse plasma control research for FNSF and ITER, however, should be initially performed in the Foundations category on existing U.S. facilities where the appropriate pioneering research is already taking place. Both DIII-D and NSTX-U have programmatic plans to advance the scientific basis of sustained plasma control of the AT and ST, respectively. In the case of the AT, the maturing knowledge and capability will be transitioned to the Asian long pulse devices (EAST, KSTAR, and ultimately JT-60SA). A DOE-funded international collaboration on plasma control on EAST and KSTAR has recently been initiated, and should be expanded later in the 10-year plan to exploit other benefits of long-pulse facilities, e.g., assessing asymptotic PMI in stationary, long pulse discharges. The outcome of control and sustainment work on the ST is discussed below. In both cases, the work is intended to enable a decision on the preferred configuration of FNSF that is expected to run continuously for weeks.

The Spherical Torus program has a special role in the U.S. program. The ST is envisioned to be a potential lower-cost experimental platform for carrying out a fusion nuclear science subprogram beyond the 10-year scope of the Panel Report. NSTX-U, when complete, will be one of two major STs in the world that can develop the scientific basis for the ST as a configuration for FNSF. A goal of the U.S. plan is to provide an informed decision within ten years on whether the preferred magnetic geometry of the FNSF should be AT, ST, or stellarator. To this end, NSTX-U should primarily focus on resolving the technical issues underpinning the FNSF-ST design. The key issues more or less specific to the ST have been identified to be non-solenoidal startup, sustainment of the plasma current, and scaling of confinement with collisionality. Additionally, LTX and Pegasus, as the supporting STs, play important supporting research in the areas of PMI and current initiation studies, respectively.

- Recommendation: *Focus research efforts on studies crucial to deciding the viability of the ST for FNSF.*

In addition to the four broad Initiatives supported by vigorous activities in Foundations, the Panel makes the following recommendations for Vision 2025:

- Focus research efforts on studies crucial to viability of the ST for FNSF.
- Resolve the major impediment to the success of ITER and to the realization of a tokamak design for FNSF and DEMO, the elimination and/or amelioration of debilitating transient events.
- Technically assess which upgrades to existing facilities or new facilities will most effectively address crucial boundary physics issues.
- Leverage activities with the broader applied mathematics and computer science communities and maintain and strengthen existing base theory and SCIDAC subprograms to maintain world leadership.
- Ensure excellence in the Experimentally Validated Integrated Predictive Capabilities program with a peer-reviewed, competitive proposal process. A community-wide process is needed to precisely define the scope and implementation strategy for ultimately realizing a whole-device predictive model.

Where we are in 2025, and future direction

ITER is expected to be operating at the end of the 10-year timeframe of this report and will be the beneficiary of all of the Initiatives described in this section. Substantial advances in the theory and practice of the control of ELMs and disruptions will allow ITER to proceed with its multiple missions with reasonable confidence that transient events are technically manageable. Increased fundamental understanding of boundary physics will allow accurate prediction of average heat loads to the divertor and pedestal height. Experimentally validated theory will be prepared to model initial ITER discharge behavior to provide essential predictive capability for future alpha-heated burning ITER plasmas that lie at the heart of that facility's goals. Looking beyond 2025, the advanced control and sustainment techniques developed on DIII-D and extended to tests on the Asian superconducting tokamaks directly contribute to the ITER mission's long-pulse discharges.

These Initiatives will also make important contributions in informing options for FNSF and providing strategies for DEMO. Successful control of transients is required if FNSF is based on a tokamak core. Solutions for the plasma-materials interface are also essential. Finally, experimentally validated integrated predictive modeling will provide a firm basis for FES's ambitious next step in the pursuit of practical fusion energy.

Chapter 3: Burning Plasma Science – Long Pulse

Definition and status

Fusion power plants based on magnetically confined plasmas are envisioned to essentially run continuously, with only short shutdown intervals for maintenance. While significant fusion output from tokamak plasmas has been achieved for periods of up to several seconds, no current experimental device can operate continuously at high plasma-confinement performance.

The plasma performance achievable in current or recent tokamak and stellarator experiments, characterized by the fusion figure-of-merit $n\tau_E T$ incorporating the plasma density n, plasma temperature T, and overall energy containment time τ_E, generally decreases as the duration of the plasma increases, (*c.f.*, Fig. 4.1 in FESAC's 2012 report on Opportunities in International Collaboration). The category of Long Pulse research encompasses the extension of high-performance plasmas to discharge durations that progressively satisfy the goals of ITER and FNSF, and project to DEMO and ultimately steady-state fusion power plants.

Superconducting magnets, radio-frequency waves, and neutral beams must be capable of confining and heating the plasma for long durations. The power provided by the heating systems, and fusion-generated alpha particles in burning plasmas, are removed from the plasma at its boundary, leading to intense interaction with the plasma-facing materials in the divertor and wall that must be better understood. As tokamak plasmas require plasma current for confinement, this must be sustained and controlled against instability for extended durations. In all burning plasma devices the most pressing overarching issue is the performance of the plasma-facing materials over time. The durations defined by the term "long pulse" in this chapter are set by the time scales of equilibration of the wall material with respect to impurity evolution and recycling of the incident plasma, thermal equilibration of the plasma-facing components, and material erosion and migration. Additional Long Pulse issues involve exploratory research on the materials, fuel regeneration, and power conversion concepts that will provide the scientific basis for the design and construction of an integrated-effects facility (FNSF). The facility is viewed as the final precursor for a demonstration fusion power plant (DEMO).

The Burning Plasma Science Long Pulse subprogram consists of five general research elements. In a coordinated activity with the Foundations subprogram, plasma physics research exploring the new and unique scientific regimes that emerge during extended plasma confinement (including regimes achieved with stellarators and long-duration superconducting international tokamaks) are being investigated. In a second element coordinated with the Foundations subprogram, a variety of plasma technology research activities on heating, fueling, and transient mitigation that enable advanced plasma physics operations are being explored; plasma technology activities related to short-pulse operations are located in the Foundations subprogram, whereas plasma technology research focusing on long pulse operations, including divertor solutions for extended operations, are organized in the Long Pulse subprogram.

A third element is devoted to materials research to understand and ultimately design high-performance materials that can withstand the harsh conditions associated with a burning plasma environment. Blanket engineering science, the fourth element, is focused on research approaches to replenish the tritium fuel and extract the fusion heat from next-step fusion burning plasma devices. The fifth element is dedicated to exploratory design studies of attractive steady-state fusion power concepts.

This subprogram currently consists of the following elements:

1) The research and operations of both major U.S. machines, the DIII-D National Fusion Facility located at General Atomics and the National Spherical Torus Experiment Upgrade (NSTX-U) at PPPL,

2) Long-pulse plasma physics research using stellarators and international superconducting tokamaks,

3) Activities in the theory and simulation and the Scientific Discovery Through Advanced Computing (SciDAC) subprograms related to long-pulse plasma operations, plasma material interactions, and fusion nuclear science issues,

4) Plasma-material interactions (PMI) and high heat flux (HHF) research for plasma-facing components during long pulse operation,

5) Materials science research to understand and mitigate property degradation phenomena associated with intense D-T fusion neutron-irradiation and to design new high-performance materials to enable practical fusion energy,

6) Blanket engineering and science to devise solutions for creating and reprocessing the tritium fuel and efficiently utilizing the deposited heat for electricity production, and

7) Development of integrated designs and models for attractive fusion power concepts.

Due to their overarching importance, plasma–material interactions and boundary plasma physics are the focus of the Interfaces Initiative, and crucial to both Foundations and Long Pulse subprograms. At present, the U.S. does not have a long-pulse facility on which long-pulse research can be carried out, although the domestic program has well-diagnosed short-pulse tokamaks that address crucial plasma physics issues for the Long Pulse subprogram. The U.S. does operate a number of single effect and few effects plasma simulators and test stands to study plasma-surface interactions (PSI) for candidate plasma-facing materials.

The major plasma simulators (PISCES, TPE) address basic PMI science topics such as sputtering, surface morphology modifications (fuzz, blisters, etc.), retention of fuel (including tritium) in various materials (including neutron-irradiated tungsten), the synergistic effects of mixed materials, and the effect of simulated ELMs. The intense plasma source for an advanced linear multi-effects plasma simulator that would simulate conditions in the divertor of an FNSF-class facility is under development. High-heat-flux test stands are currently being used to study the effects on materials properties in neutron-irradiated materials samples and to study, on a small scale, various helium jet-impingement cooling concepts proposed for PFCs. The U.S., in its theory and simulation subprogram, maintains a comprehensive modeling and validation effort in the areas of boundary physics; material erosion, migration of and redeposition; and plasma instability-induced materials damage.

Structural materials, blanket development, and tritium handling are key elements of the FNS Initiative. The U.S. is a leader in the area of reduced-activation structural materials , with the leading international reduced-activation structural material candidates all derived from U.S. concepts. Broad materials science expertise and advanced neutron irradiation and characterization facilities are currently available due to leveraging of other DOE programs, and a near-term high-intensity irradiation facility that provides fusion-relevant neutron irradiation spectra based on existing spallation (high energy accelerator) concepts is under development. The U.S. also has significant capabilities in fusion blanket development (modeling and experiments); surface heat flux handling; tritium processing, permeation and control; safety/accident event analysis; and power plant design and modeling.

The generation of long pulse toroidal plasmas that serve as the target of this work will take place in tokamaks and stellarators. The U.S. program places a priority on developing the scientific basis for extending the pulsed tokamak to operate continuously, or at least for the duration required for FNS-relevant PMI studies. This research implements control theory and modeling and plasma actuators in the form of radio frequency current drive and tangentially–oriented neutral beams to maintain and control the plasma current profile necessary for stable confinement of a tokamak plasma. U.S. researchers are leaders in this novel approach and should continue to make progress for several years on the well-diagnosed DIII-D and NSTX-U facilities, as discussed in the previous chapter. Because the U.S. has no long-pulse facility on which true steady-state research can be carried out, the Panel expects that after about five years these efforts will increasingly transition from the domestic facilities with plasma durations of several seconds, to superconducting long pulse tokamaks in China, South Korea, and Japan with plasma pulse lengths of 100 seconds or more. Collaborations in control and sustainment are already underway with EAST and KSTAR. These collaborations should ultimately expand to ones based on solving long pulse PMI issues.

The stellarator is widely viewed as the second-most developed fusion plasma concept, after the tokamak. Unlike the tokamak, it operates intrinsically in steady state and to date has proven to be disruption-free. The U.S. has remained active in stellarator research through a small, but vibrant, theory and simulation subprogram, small university-scale domestic experimental facilities and collaborations with Japan's Large Helical Device (LHD), and a flourishing partnership with Germany's new Wendelstein 7-X project. The German partnership allows the U.S. to play an important role, with leadership potential, in international stellarator research.

Although the U.S. does not have a long-pulse facility on which steady-state research can be carried out, U.S. scientists are working on long-pulse Asian tokamaks in the areas of current-drive actuators and diagnostics, as well as on control scenarios and control techniques.

Thrusts

Of the eighteen MFE-ReNeW Thrusts, ten are relevant to the Long Pulse theme. Details of those Thrusts – 4, 5, 7, 10, 11, 12, 13,14,15, and 17 – can be found in Chapter 2.

There are eight Thrusts unique to Long Pulse, along with the two Thrusts led by Foundations that involve some Long Pulse aspects. In addition, Thrust 9, allocated to Foundations, is so closely related to Thrusts 10-12 that they were considered together in the ReNEW report under the MFE-ReNeW theme, "Taming the plasma–material interface."

Within the Foundations and Long Pulse subprograms, the Interfaces Inititative emerged as a Tier 1 Initiative. It should be noted that Thrust 9 deals with the interaction between core plasma, scrape-off layer, and wall. Thrust 12 includes a focus on PMI-core integration, while Thrusts 10 and 11 address high plasma erosion, heat-flux challenges, and potential innovative design solutions. Within the Interfaces Initiative, the focus of the Long Pulse subprogram is on Thrusts 10 and 11.

Similarly, the MFE-ReNeW report collectively considered Thrusts 13-15 under the MFE-ReNeW theme, "harnessing fusion power." These areas together comprise the Tier 2 FNS Initiative recommended by the Panel. The Panel report emphasizes Thrusts 13 and 14 in the first phase, while Thrust 15 becomes more important in the second phase (nominally the last five years) of the FNS Initiative.

Priorities

The Long Pulse subpanel determined that Thrust 10 was the highest priority activity because of the urgency of addressing the threats posed by the combined high heat and particle fluxes on PFCs, relevance to ITER, and the opportunity for U.S. leadership. Thrust 14 was considered to be the next highest priority because multiple materials issues were considered to be crucial to the advancement of fusion nuclear science, the strong opportunity for U.S. leadership, and multiple opportunities for leveraging with other Federal Programs as noted in Chapter 5 and Appendix G. Finally, Thrust 17 was considered to be important to Long Pulse because of its relevance to fusion nuclear science, the maintenance of U.S. leadership, its utilization of U.S. strengths and the potential to address unique interface issues (Thrust 10) associated with three-dimensional configurations. The research of Thrust 17 and the advanced tokamak development discussed in Chapter 3 together constitute an important aspect of long pulse research: how to create a high performance plasma that has sufficiently long duration, as needed for future fusion-energy machines.

To help in ranking these Thrusts, the Long Pulse subpanel identified a number of basic science questions to be addressed within each Thrust. Those identified for Decoding and advancing the science and technology of PSI [Thrust 10] were:

• How does neutron irradiation influence erosion yields, dust production and tritium retention in PFCs?

• How do PFCs evolve under fusion prototypic fluxes, fluences and temperatures?

• What determines the lifetime of a PFC? For example, is net erosion yield due to physical sputtering, macroscopic erosion leading to dust (e.g. delamination of surface films, unipolar arcing of nano-structures, bursting blisters, whole grain ejection) or melt layer loss?

• Is there a viable option for a robust helium-cooled tungsten PFC capable of withstanding steady-state and transient high heat fluxes?

• Are PMI solutions for low net divertor erosion during long pulse plasma exposure compatible with an optimized core plasma? How do the resulting thick redeposited surface layers evolve and what are their thermal and mechanical properties?

The basic science questions for developing the materials science and technology needed to harness fusion energy [Thrust 14] were:

• Is there a viable structural material option that might survive the DT fusion irradiation environment for at least 5 MW-yr/m^2 (50 displacements per atom)?

• What are the roles of fusion-relevant transmutant H and He on modifying the microstructural evolution of irradiated materials?

• What is an appropriate science-based structural design criterion for irradiated structural materials at elevated temperatures?

The science questions for optimizing steady-state, disruption-free toroidal confinement [Thrust 17] were:

• What tokamak heating and control solutions are most effective in realizing stable long pulse tokamak discharges?

• What stellarator divertor solutions are capable of high power handling and power control in long-pulse operational scenarios?

• Can PMI solutions be integrated with high performance, steady-state core stellarator and advanced tokamak plasmas?

Initiatives

Of the four highest-priority Initiatives identified by the Panel, the Interfaces and FNS Initiatives are the most relevant to Long Pulse, in addition to the cross-cutting Predictive Initiative. As highlighted in prior community evaluations, including the MFE-ReNeW assessment and 2007 and 2012 FESAC panels (ref. Greenwald, Zinkle), arguably the most daunting near-term challenge to establishing the technological feasibility of magnetic fusion energy is finding a solution for the plasma-materials interaction (PMI) challenges. These challenges for long-pulse burning-plasma operation include:

• potentially unacceptable material erosion and redeposition from intense particle fluxes,

• undesirable tritium entrainment in redeposited layers, and

• high heat-flux melting of plasma facing armor and associated thermal fatigue damage to underlying structures.

All of these challenges could lead to unacceptable failures and require frequent replacement of PFCs. In all cases, the solution to the PMI challenges needs to be compatible with an optimized core plasma. Several potential approaches for mitigating some of these PMI effects have been proposed (e.g., plasma-based configurational changes, material modifications), but they all need to be vigorously explored and eventually validated on appropriate PMI facilities.

Although a number of long-pulse tokamaks have or will start operation over the next decade outside the U.S., control of plasma equilibrium and impurity influx of high performance long-pulse discharges, required for successful operation of long-pulse facilities, has not been satisfactorily demonstrated in any device to date. Over the next ten years, studying plasma control will be an important research activity in both U.S. and international facilities.

The overarching limitation in any magnetic confinement configuration is the intolerably high power loading/PMI at the first wall and divertor. ITER-level power fluences in reactor-relevant divertors have been studied in the Alcator C-Mod tokamak, which is expected to be shut down. State-of-the-art plasma control techniques with various current and profile actuators, required for long-pulse advanced tokamak plasmas, are being pioneered on the DIII-D tokamak. Several other toroidal PMI devices have been proposed, as documented in the community input to the FESAC SP panel (Appendices E and F). At a much smaller scale, preparatory work on three-dimensional edge transport can be performed on U.S. university short-pulse stellarators in support of evaluating boundary transport models.

The Panel concluded that the most cost-effective path to finding a self-consistent solution to the daunting PMI challenge was to construct an advanced multi-effects linear divertor simulator that can test PFC materials at prototypical powers and fluences. One of the new classes of advanced linear PSI facilities called for in Thrust 10, a linear divertor simulator, is defined here to be a facility that operates at the very high fluence conditions expected at the divertor target in DEMO (or FNSF). This facility would explore PMI for long-duration pulses (up to one million seconds) in the low net erosion regime and perform accelerated end-of-life testing of candidate PFCs. The facility will operate at thermal plasma parameters (ion flux, temperature, and density) that will allow investigation of prompt redeposition of sputtered atoms to dramatically reduce net erosion rates. It should also test neutron-irradiated materials to explore synergistic effects due to material thermo-physical properties changes and trapping of fuel on damage sites. Results from this facility, along with those from numerical simulations, will inform PFC development for and operations on long-pulse tokamaks.

The FNS Initiative will establish a fusion nuclear sciences subprogram, which is required to address key scientific and technological issues for harnessing fusion power (materials behavior, tritium science, chamber technology, and power extraction). Determining how the materials in contact with the fusion plasma and the underlying structure are affected by extreme heat and particle fluxes while simultaneously suffering neutron radiation damage, and developing practical approaches to managing the tritium fuel cycle are both required for practical fusion energy. The unique changes to materials and components due to exposure to the fusion reactor environment (ranging from PFCs to structural materials to breeding blankets and tritium extraction systems) need to be understood in order to provide the scientific basis for fusion energy.

The ultimate goal of the FNS Initiative is to provide the scientific basis to design and operate an integrated FNSF. When completed, it would be a research facility that incorporates most of the technical components within the core of a future DEMO power plant, but is built at minimum fusion power in order to enable fusion component testing and optimization at minimum tritium consumption and overall cost [Goldston, FESAC, 2003]. There are several crucial near-term decisions that will shape the FNSF design. The plasma configuration (AT, vs. ST tokamak, vs. stellarator) and operational regimes need to be established on the basis of focused domestic and international collaborative long-pulse, high-power research. Materials science research needs to be expanded to comprehend intense fusion neutron irradiation effects on property degradation of structural materials and to design potential materials science approaches to mitigate these degradation phenomena. The Panel concluded that building a new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source would be a highly cost-effective option for this purpose.

Fundamental research is also needed to identify a practical tritium fuel and power conversion concept, including improved understanding of tritium permeation and trapping in candidate coolants and fusion materials, exploration of viable methods for efficiently extracting tritium from hot flowing media, and improved understanding of complex magnetohydrodynamic effects on the flow of electrically conductive coolants in confined channels. Diagnostics appropriate for FNSF conditions will also need to be developed by leveraging the experience and diagnostics development that comes from ITER.

Axisymmetric (tokamak and ST) configurations are the best understood options for a next-step facility. The non-axisymmetric optimized stellarator is less well developed in absolute level of plasma-confinement performance but avoids some of the tokamak's challenges in that stellarators are inherently steady-state, operate at relatively high plasma density, provide greater design flexibility in their magnetic configuration, and do not suffer from disruptions or large ELMs. Depending on progress resolving crucial long pulse science issues with regard to ATs and STs, the U.S. should consider expanding the stellarator subprogram in Phase 2 by constructing an experiment with sufficient performance to establish the confinement of an optimized stellarator based on quasi-symmetry principles. This activity could eventually lead to a steady-state nuclear facility based upon the stellarator, if needed.

Future Perspective in 2025

The subprogram elements of the Long Pulse highest-priority research are guided by a 2025 Vision that will enable successful operation of ITER with U.S. participation; provide the scientific basis for a U.S. Fusion Nuclear Science Facility (FNSF); and create a U.S. "Generation ITER-FNSF" workforce that can lead scientific discoveries and technological innovation. The Interfaces Initiative contributes to the successful operation of ITER; the Interfaces and FNS Initiatives will together establish the scientific basis of FNSF. Finally, the research supported by these Initiatives will train a significant portion of the Generation ITER-FNSF fusion workforce.

Ten years after Vision 2025 is initiated, the specific deliverables of the Long Pulse subprogram are:

- The Interfaces and FNS Initiatives have identified scientifically robust solutions for long pulse DT burning plasma machines.
- The advanced linear divertor simulator is operating at full capability and is a world-leading user facility providing scientific insight on PMI mechanisms and potential solutions.
- The preliminary science basis for viable structural materials for FNSF and DEMO has been established using a fusion materials neutron-irradiation test stand.
- The basic plasma configuration and geometry of FNSF has been decided, and design is underway based on new scientific knowledge of highly stable long pulse plasma configurations, high performance materials systems, innovative fusion blanket systems, and proven tritium extraction techniques.
- Optimized stellarator plasmas suitable for long-pulse operation, with the capability to handle appropriate wall and divertor loads, have been demonstrated in integrated tests.
- The scientific principles of long-pulse advanced tokamak operation are established.

In ten years, the Panel envisions that ITER will have achieved first plasma. Although this subprogram focuses upon confinement configurations with pulse durations of at least one million seconds, ITER first plasma effectively marks the beginning of the magnetic fusion energy era. With the Interfaces and Fusion Nuclear Science Initiatives, the U.S. will be ready to lead in the following areas of fusion nuclear sciences:

- plasma boundary and plasma-material interactions
- advanced high-heat-flux plasma-facing components
- innovative blanket concepts including reduced-activation structural materials
- optimized three-dimensional plasma geometries.

By investing in these areas, the U.S. will be ready to design and build a world-leading fusion nuclear sciences facility that will be the bridge required to go from ITER to a reactor that will demonstrate practical magnetic fusion energy.

Supporting Recommendations

The specific recommendations for Long Pulse are:

- Design and build the advanced multi-effects linear divertor simulator described above to support the Interfaces Initiative.

- Design and build a new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source to support the Fusion Nuclear Sciences Initiative.
- Invest in a research subprogram element on blanket technologies and tritium sustainability that will advance studies from single to multiple effects and interactions.

Chapter 4: Discovery Plasma Science

DPS Definition

The purpose of Discovery Plasma Science (DPS), as described by the Fusion Energy Science program, is to "increase the fundamental understanding of basic plasma science, including both burning plasma and low temperature plasma science and engineering, to enhance economic competiveness and to create opportunities for a broader range of science-based applications."

The DPS description in the April 2014 Charge Letter to FESAC is "the study of laboratory plasmas and the HED state relevant to astrophysical phenomena, the development of advanced measurement for validation, the science of plasma control important to industrial applications."

The NRC Plasma 2010 Plasma Science Committee report [Ref. 1, Appendix H] provided descriptions of plasma science and engineering research, opportunities, and applications for the following plasma science fields: Low-Temperature Plasma Science and Engineering, Plasma Physics at High Energy Density, The Plasma Science of Magnetic Fusion, Space and Astrophysical Plasmas, and Basic Plasma Science.

With the aid of all three descriptions above, the definition the Panel used to guide subsequent DPS discussions is:

- Discovery Plasma Science stewards plasma innovation and applications by expanding the understanding of plasma behavior in concert with training the next generation of plasma scientists to help ensure the continuation of U.S. leadership.

DPS Status

In FY14, the DPS subprogram had a total funding of $45.7M that supported approximately 90 university grants and 45 DOE national laboratory projects. The FY14 DPS subprogram elements had the following funding levels:

• General Plasma Science	$15.0M
• HED Laboratory Plasmas	$17.3M
• Experimental Plasma Research (EPR)	$4.2M
• Madison Symmetric Torus	$5.7M
• Diagnostic Measurement Innovation	$3.5M

Recently, EPR and Madison Symmetric Torus subprogram elements were combined under the description Self-Organized Systems (SO-Systems). A brief summary of the research being explored within the individual DPS subprogram elements is:

• General Plasma Science (GPS) covers a broad set of topics in plasma science, including research into fundamental plasma properties driven primarily through discovery-based investigations. In addition to FES funding, GPS is also supported through the NSF-DOE Partnership in Basic Plasma Science and Engineering [Ref. 2, Appendix H]. The breadth of GPS research topics can be represented in part by workshops involving the plasma research community that explored opportunities in low temperature plasma science [Ref. 3, Appendix H] and plasma astrophysics [Ref. 4, Appendix H]. The GPS portfolio includes research teams that are best described as Single Investigator, Centers/Collaborations, and User Facilities. As a representative example of GPS plasma research, the list of publications associated with the Basic Plasma Science Facility at UCLA [Ref. 5, Appendix H], and the list of research highlights associated with the Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems at the University of Michigan [Ref. 6, Appendix H] are referenced (Appendix H).

• High Energy Density Laboratory Plasmas (HEDLP) refers to the study of plasmas at extremely high density and temperature corresponding to pressures near one million atmospheres. The FES HEDLP research is focused on HED science topics without any implied specific applications. As a HEDLP partnership between BES and FES, the Matter at Extreme Conditions (MEC) end station of the Linac Coherent Light Source (LCLS) user facility at SLAC provides scientific users with access to HED regimes uniquely coupled with a high-brightness x-ray source [Ref. 7, Appendix H]. HEDLP research is also carried out within the NSF-DOE Partnership and the NNSA SC HEDLP Joint Program. As a representative example of HEDLP research, the list of publications associated with the LCLS MEC is referenced [Ref. 8, Appendix H].

• Self-Organized Systems activities include plasma physics and technology activities germane to the understanding of magnetic confinement and to improving the basis for future burning plasma experiments (see the 2008 FESAC Toroidal Alternates Panel, Ref. 9, Appendix H). SO-Systems has a great deal of overlap with GPS research given that GPS research is performed on many of the SO-Systems experiments with direct and indirect application both to non-fusion GPS plasmas, as well as fusion relevant plasma topics such as magnetic configurations, stability, electrostatic and magnetic turbulence and transport, current drive, and many others. The Madison Symmetric Torus experimental facility at the University of Wisconsin supports both Reversed Field Pinch investigations and basic plasma physics research [Ref. 10, Appendix H]. The facility engages a large number of postdoctoral researchers, graduate students, and undergraduate students in both fusion science and plasma physics research. The list of publications associated with the Madison Symmetric Torus exemplifies the productivity of the SO-Systems subprogram element [Ref. 11, Appendix H].

• Diagnostic Measurement Innovation (DMI) supports validation-related diagnostic development that couples experiments, theory, and simulation to improve models of plasma behavior in fusion research devices, and to monitor plasma properties and act upon feedback control signals in order to improve device operations. Every two years, the High-Temperature Plasma Diagnostic (HTPD) conference brings together diagnosticians representing all three FES subprograms who then publish findings in the journal *Review of Scientific Instruments* [Ref. 12, Appendix H]. The European Physical Society Conference on Plasma Diagnostics series is modeled on the U.S. conference and takes place in years alternate to HTPD.

DPS Prioritization and Recommendations

Within the DPS program elements (GPS, HEDLP, Self-Organized Systems, and Diagnostic Innovation), there is a broad spectrum of plasma regimes with a correspondingly wide range of plasma parameters. References include previous reports (e.g. FESAC) and workshops (e.g. ReNeW) relevant to DPS, the NRC Plasma 2010 report, and the 2014 DPS community presentations and white papers. The DPS subpanel provides a Primary Recommendation for all of DPS and a Supporting Recommendation for each DPS subprogram element.

A finding from the Plasma 2010 report is especially germane to the prioritization process and worth noting here:

"The vitality of plasma science in the past decade testifies to the success of some of the individual federally supported plasma-science programs. However, the emergence of new research directions necessitates a concomitant evolution in the structure and portfolio of programs at the federal agencies that support plasma science. The committee has identified four significant research challenges that federal plasma science portfolio as currently organized is not equipped to exploit optimally. These are fundamental low-temperature plasma science, discovery-driven high energy density plasma science, intermediate-scale plasma science, and cross-cutting plasma research."

The DPS subpanel sorted the 20 DPS white papers into their respective DPS program elements, evaluated the contributions using the following set of prioritization metrics, and arrived at the DPS Primary Recommendation:

DPS Prioritization

• Advancing Plasma Science Frontiers: Whether the DPS research priority proposed would advance the frontiers of plasma innovation and plasma applications

• Strengthening Collaborations: Whether the DPS proposed investment could lead to collaborations between universities, national laboratories and industry, and across federal agencies

• Providing Cross Cutting Benefits: Whether the DPS investment would provide cross cutting benefits to all FES programs especially in training the next generation of plasma scientists

DPS Primary Recommendation:

• *FES stewardship of basic plasma research should be accomplished through strengthening of peer-reviewed university, national laboratory, and industry collaborations. In order to realize the broadest range of plasma science discoveries, the research should be enhanced through federal-agency partnerships that include cost sharing of intermediate-scale, collaborative facilities*

In addition to the Foundations and Long Pulse Tier I and Tier II Initiatives, the expanded description of the DPS Primary Recommendation "Advancing the frontiers of DPS knowledge through highly leveraged, collaborative facilities" is provided:

• Effective DPS program elements can provide transformational and sometimes disruptive new ideas for plasma topics. DPS research seeks to address a wide range of fundamental science, including fusion, but the topics selected are those outlined by the NRC Plasma 2010 report. DPS activities are synergistic with the research mission of other federal

agencies and significant opportunities exist to broaden the impact of DPS through the development and expansion of strategic partnerships between FES and other agencies. Addressing fundamental science questions at the frontier of plasma science requires a spectrum of laboratory experimental facilities from small-scale, single-PI facilities to intermediate-scale, highly collaborative facilities. The development of each intermediate-scale and multi-investigator facility with world-leading capabilities will address a range of cutting-edge scientific questions with a comprehensive diagnostic suite. Mutual interactions between larger facilities found at national laboratories and small and intermediate facilities will facilitate the advancement of DPS frontiers, conducted on the smallest appropriate scale, and in training the next generation of plasma scientists.
The absence of DPS-specific Initiatives is intentional in order to avoid any potential misinterpretations of the paradigm that was used to map the Foundations and Long Pulse Initiatives with the full set of 18 ReNeW MFE Thrusts. The one outlier is Thrust 18, "Achieve high performance toroidal confinement using minimal externally applied magnetic field," which represents a portion of projects in the SO-Systems element of the DPS subprogram.

The Primary Recommendation above and the following Supporting Recommendations are envisioned aggregately as supporting the DPS definition. The DPS prioritization process also included Supporting Recommendations.

DPS Supporting Recommendations

General Plasma Science (GPS) Supporting Recommendation:

• *FES should take the lead in exploring multi-agency partnering for GPS activities. This effort should include funding for intermediate-scale facilities (as discussed in the NRC Plasma 2010 report) with funding for construction, operations, facility-staff research, and the corresponding user research program.*

The intermediate-scale facilities should be either: strongly collaborative in nature, involving researchers from multiple institutions working on experiment, theory and simulation, or operate as open user facilities, offering research opportunities to researchers from a broad range of institutions. At the same time, the investment strategy aimed at increasing the number of intermediate-scale facilities should not lose sight of noteworthy contributions coming from small-scale facilities and plasma centers. The natural partnering opportunities for FES to explore are between the DOE Office of Science (SC) and the National Nuclear Security Administration (NNSA), as well as other relevant federal agencies. Two current partnership models are the National Science Foundation-DOE Partnership in Basic Plasma Science and Engineering, and the NNSA-SC Joint Program in HED Laboratory Plasmas. One resource to use for leverage is the NSF Major Research Instrumentation Program for facility construction funding [Ref. 13, Appendix H]. That source was used to partially fund the construction of the BaPSF [Ref. 14, Appendix H] and more recently for the advanced reconnection facility FLARE [Ref. 15, Appendix H], the plasma dynamo facility MPDX [Ref. 16, Appendix H], and the magnetized dusty plasma facility MDPX [Ref. 17, Appendix H].

High Energy Density Laboratory Plasmas (HEDLP) Supporting Recommendation:

• *FES should avail itself of levering opportunities at both SC and NNSA high-energy-density-physics user facilities, within the context of the NNSA-SC Joint Program in HEDLP. This is especially true for the FES HEDLP community researchers who have been* *awarded experimental shot time, much as FES avails itself of the levering opportunities within the highly successful SciDAC partnership between ASCR and FES.*

The Panel's recommendation is consistent with the opportunities outlined in both the HEDLP Basic Needs Workshop report (November 2009, Ref. 18, Appendix H) and the FESAC HEDLP Panel report (January 2009, Ref. 19, Appendix H), and warrants consistent and appropriate funding for proposal-driven competitive HEDLP research.

Self-Organized Systems Supporting Recommendation:

• *FES should manage the elements of SO-Systems using subprogram-wide metrics with peer reviews occurring every three to five years to provide a suite of capabilities that explore an intellectually broad set of scientific questions related to self-organized systems.*

The experimental flexibility and diagnostic sets on SO-Systems experiments makes these facilities valuable for predictive-model validation test beds. FES should take the lead for exploring multi-agency partnering for SO-Systems activities.

Diagnostic Measurement Innovations Supporting Recommendation:

• *FES should manage diagnostic development and measurement innovation in order to have a coordinated cross-cutting set of predictive model validation activities across all DPS subprogram elements: GPS, HEDLP, and SO-Systems.*

Diagnostic development and measurement innovation should be a shared, crosscutting program with easy transitions between subprogram elements to allow rapid development, sometimes starting on small to intermediate-scale devices and, when appropriate, further development of the innovative measurement techniques on BPS Foundations and Long Pulse facilities.

DPS and Budget Scenarios

Because of the FES's stewardship of DPS subprogram elements across year-to-year variations in funding in the series of presidential budget requests and Congress-enacted budgets, the Panel's recommendations for DPS funding levels associated with the Charge Letter's four budget scenarios were done for the DPS subprogram as a whole, rather than for individual DPS subprogram elements (GPS, HEDLP, SO-Systems, and Diagnostic Development and Measurement Innovation).

For the funding associated with the highest-level budget of the Charge Letter's four scenarios [FY14 ($305M) with Modest Growth], funding is envisioned for the DPS Supporting Recommendations, as well as the DPS Primary Recommendation. The intermediate-scale investments during the Phase I and Phase II (see Executive Summary) should include funding for construction, yearly operations, facility-staff research, and research program user support. Even with the advantage of multi-agency cost sharing, the need will arise for significant investments from FES to provide a suite of intermediate scale facilities as proposed by different plasma subfields within DPS. The addition of new, intermediate-scale facilities should be managed by a peer-reviewed process cognizant of the strategic directions for FES, and by a staged construction approach consistent with the mortgage that each facility will create.

For the funding associated with the lowest-level budget scenario (FY15 President's request [$266M] with cost of living increases), the Panel recommends reducing the number of DPS plasma subfields in order to maintain the world-class quality of the remaining subfields. The process for restricting which subfields would remain in the DPS portfolio, and which would not, could include criteria that are identified in the NRC Plasma 2010 report, and/or that consider which subfields have a strong focus in other federal agencies. To establish the criteria that would best serve the FES stewardship of plasma science, SC should consider a FESAC review of the wide breadth of plasma subfields and facilities within the DPS portfolio using the criteria of being identified in the NRC Plasma report, of having a strong focus in other federal agencies, and of earning a national and international reputation for excellence. A future FESAC DPS portfolio review will provide an additional and complementary perspective to activities associated with the FESAC Committee of Visitors with the FESAC goal to examine the optimization of a balanced DPS portfolio with leveraged, high-impact discovery science through collaborations on state-of-the-art facilities [Ref. 20, Appendix H].

For the funding associated with the middle-level budgets of the Charge Letter's scenarios [(2)–FY14 ($305M) with cost of living, and (3)–FY14 ($305M) flat funding], the Panel recommends a compromise between the high- and low-budget scenarios above.

DPS 2025 and Beyond

Leading up to 2025, FES workforce development needs should be integral to all DPS recommendations because of the large percent of DPS projects that involve graduate student PhD thesis research, which directly benefits DPS research. Workforce development also provides the training and experience necessary to develop the next generation of plasma and fusion researchers for all FES subprograms.

By 2025, the major FES facilities should have a DPS User Community role per the SC description of User Facilities and User Programs [Ref. 21, Appendix H]. This 2025 DPS strategy was not an explicit DPS recommendation because such a strategy would need to be fully integrated into the Foundations and Long Pulse research plans for the major FES facilities.

Chapter 5: Partnerships with Other Federal and International Research Programs

Introduction

The DOE Office of Fusion Energy Sciences has a longstanding practice of reaching out to other federal and international research programs to establish partnerships. For example, FES was responsible for the conception and implementation of leadership-class high-performance computing national user facilities, begun 40 years ago with the creation of the National Magnetic Fusion Energy Computer Center, the forerunner to the National Energy Research Supercomputer Center. In addition to their work on domestic experiments, scientists from the FES program participate in scientific experiments on fusion facilities abroad. International partnerships are needed more than ever today as new state-of-the-art fusion facilities are at a scale that requires capital and operational resources beyond what a single nation can afford.

The Panel was tasked to provide an "assessment of the potential for strengthened or new partnerships with other federal and international research programs that may foster important opportunities otherwise unavailable to U.S. fusion scientists…." Such strategic partnerships will be critical to accomplishing the report recommendations, delivering on the full potential of the Initiatives, and realizing Vision 2025.

Evaluation Process & Prioritization Criteria

The Panel examined a wide range of potential partnerships against those four criteria:

1. Importance and urgency, consistent with Vision 2025.
2. Return on FES investment, including cost share, cost avoidance through in-kind contributions, risk reduction, and accelerated progress to meet Vision 2025.
3. Sustained & expanded U.S. leadership in strategic areas associated with the four priority Initiatives and Discovery Plasma Science.
4. Clear mutual benefit, which we define as both parties receiving value that they would normally be unable to produce on their own; bringing complementary strengths to the partnership; having a stake in the other's facilities and program; and respecting each other's cultural differences in how the partnership is justified.

The Panel's findings are summarized below in two tables: Partnership and levering opportunities within other DOE and federal programs (Table I); and opportunities for U.S. participation in international facilities (Table II). Detailed descriptions of the partnerships with DOE and federal programs can be found in Appendix G.

Federal Partnership Opportunities

Numerous federal agencies, covering a wide range, were considered for possible partnerships by the Panel (Table I). Extended comments are provided for the most promising opportunities relevant to the proposed 10-year plan.

Table 1: Federal Agencies with complementary programs relevant to FES.[1]

Federal Program	FES Themes Benefitting	Current Partnership Status	New or Expanded Opportunity Level	Comments
DOE OFFICE OF SCIENCE				
Advanced Scientific Computing Research (ASCR)	F, LP, DPS	Moderate-Strong	High	Exemplary relationship resulting in U.S. leadership in fusion theory, simulation, and computation. Future SciDAC opportunities for DPS are also evident (cf. Ch. 4)
Basic Energy Sciences (BES)	LP	Moderate	Medium to High	Joint operations of the LCLS MEC Station and longstanding fusion materials irradiation programs using BES reactor neutron sources. Materials Science PI-to-PI interactions evident in core FES programs and BES Energy Frontier Research Centers. Mutual benefits of spallation-neutron-sources use for fusion materials irradiation studies need to be evaluated.
High Energy Physics (HEP)	LP DPS	Minimal	Medium	Modest overlap in plasma science (advanced accelerator and HEDLP) and fusion technology (high-temperature superconducting magnets).
Nuclear Physics (NP)	LP	None	Medium	New Nuclear Physics Program identifies Nuclear Engineering and Applications as a primary client for nuclear data.
OTHER DOE PROGRAMS				
Advanced Research Projects Agency – Energy (ARPA-E)	DPS	Minimal	Unknown at this time	New program announced in Aug. 2014.
Energy Efficiency and Renewable Energy	LP	None	Medium	Supports fundamental investigations of additive manufacturing for producing high-performance components that would be

[1] "F" stands for Foundations, "LP" for Long Pulse, and "DPS" for Discovery Plasma Science. A "low" opportunity corresponds to meeting one or fewer of the four Panel prioritization criteria, a "medium" meets two or three criteria, while a "high" meets all four criteria.

(EERE)				difficult or impossible to fabricate using conventional means.
Fossil Energy (FE)	LP	Minimal	Medium	Supports leading approach for developing new steels in both fossil and fusion energy systems based on computational thermodynamics and thermomechanical treatments.
Nuclear Energy (NE)	LP	Moderate	High	Provides infrastructure, materials programs, and nuclear regulatory expertise that should be of significant value to FES as it moves toward an FNS Program.
Nat. Nuclear Security Administration (NNSA)	DPS	Moderate	Medium to High	NNSA-ASCR partnership to develop the next generation computing platforms enables fusion scientists to maintain world-leading capability. Significant HEDLP discovery science opportunities exist on world leading NNSA-operated laser and pulsed-power facilities.
OTHER FEDERAL PROGRAMS				
Dept. Of Defense (DOD)	DPS	Minimal	Low	DOE supports individual HEDLP and ICF projects on DOD facilities. Otherwise, missions are non-overlapping.
Nat. Aeronautics & Space Administration (NASA)	DPS	None	Low	Non-overlapping missions but shared interest in high-heat flux technologies and high-temperature structural materials.
Nat. Inst. of Standards & Technology (NIST)	DPS	None	Low	Complementary materials R&D spanning nanoscience materials to advanced manufacturing.
Nat. Science Foundation (NSF)	DPS	Strong	High	Exemplary relationship, with further opportunities for new Joint programs for research and intermediate-scale facilities.

ITER Partnership

While the ITER project and operation are not part of the DOE Charge, the Panel recognizes the important partnership between the U.S. and ITER, which includes:

1. Supporting ITER design and successful completion: In addition to its direct contributions and procurements to ITER, the U.S. is expected to continue being a strong contributor in some areas of ongoing research in support of ITER's design during construction, including deployment and demonstration of the efficacy of scaled prototypes of U.S. deliverables. Some of these areas are: disruption prediction, avoidance, and mitigation, ELM control and ELM-free operating scenarios, developing ITER-like operating scenarios, and demonstrating heating, fueling, current drive and plasma control schemes, simulations and modeling.

2. Preparing for leading roles in the ITER research program: The U.S. has traditionally been among the leaders in ongoing fusion science research, which serves to prepare scientists to play leading roles in the scientific productivity on ITER. The U.S. has been a major participant in the International Tokamak Physics Activity (ITPA) due in large part to technical contributions from C-Mod, DIII-D, NSTX, and the U.S. theory and simulation subprogram. Nevertheless, research leading toward and beyond ITER could take advantage of the new capabilities under construction or already in operation in the international landscape. U.S. capabilities over the next decade, together with international collaborations in areas where the U.S. can have a partner role, will allow the domestic program to advance the Foundations-related Thrusts while preparing and maintaining the workforce that will play a key role in ITER productivity.

3. Positioning the U.S. to benefit from the results of the ITER research program: A successful ITER research program, along with parallel progress in the FNS Initiative, will provide much of the basis needed to proceed to a fusion DEMO. To position the U.S. to benefit from ITER results and proceed toward energy development requires growing a strong domestic program in fusion nuclear science. At the same time, the U.S. must

maintain leadership in the areas of theory and simulation, in materials science, and in technology.

International Partnership Opportunities (Non-ITER)

Two thorough assessments of international collaboration opportunities were recently conducted by a community task force commissioned by the U.S. Burning Plasma Organization in 2011 and by FESAC in 2012 [Appendix H]. Although neither of these studies considered trade-offs between domestic and international programs in the context of constrained FES budgets, their recommended modes of collaboration, research priorities, and evaluation criteria served as a basis for the Panel's strategic planning.

Building upon the 2012 FESAC report, the Panel spent considerable time comparing and contrasting FES international collaborations with those supported by the DOE High Energy Physics (HEP) Program. A majority of high energy physicists in the U.S. perform research at international facilities. In contrast, FES participation in international experiments is an order of magnitude lower.

International collaborations have been useful for the design of fusion neutron sources such as the proposed International Fusion Materials Irradiation Facility (IFMIF), based on an earlier U.S. design. There are potential opportunities for U.S. fusion researchers to gain access to unique foreign facilities, such as: (1) large scale corrosion and thermomechanical test loop facilities; (2) high heat flux and plasma material interaction facilities, tokamak diverter exposure facilities (WEST, EAST, ASDEX, etc; (3) future possible fusion neutron irradiation facilities such as IFMIF: (4) tritium facilities; and (5) collaborations with operational, safety and regulatory experts on how to best develop a performance-based regulatory basis for fusion power (Canada, IAEA, JET, ITER).

The Max Planck-Princeton Center for Plasma Physics, which has the mission of making greater use of the synergies between fusion research and astrophysics, is a formal partnership supported by FES that cuts across Foundations and DPS.

The table below shows summary and status of partnerships with large international devices.

Table II: International partnership opportunities.[2]

Major Foreign Facilities	First Plasma or Beam on Target	First Plasma after last major upgrade	Current Partnership Status	Initiative Contribution	Capability
ASDEX Upgrade Tokamak (Germany)	1991		Minimal	Integrated Prediction	Excellent diagnostics
EAST Tokamak (China)	2007	2014	Strong	Interface, Transients	Superconducting long pulse tokamak; hot W divertor
JET Tokamak (UK)	1983	2012 (ITER-like Wall)	Minimal	Fusion Nuclear Science	D-T experiments with Be/W wall
JT60 Tokamak (Japan)	1985	2019 JT60-SA	None	Integrated Prediction	Advanced superconducting tokamak, size scaling
KSTAR Tokamak (S.Korea)	2008		Moderate	Interface, Transients	Superconducting long pulse tokamak
LHD Stellarator	1998	2013 Helical divertor	Moderate	Interface	Superconducting long pulse stellarator with helical divertor
MAST Spherical Torus (UK)	1999	2015	Moderate	Interface	Super-X divertor
Tore Supra Tokamak (France)	1988	2015 (WEST)	None	Interface	Superconducting long pulse tokamak
W7-X Stellarator (Germany)	2015		Strong	Interface, Integrated Prediction	Superconducting long pulse stellarator with island divertor

Initiative-Relevant Partnerships:

The Panel acknowledges the informal efforts of fusion scientists who, on their own initiative, collaborate and network with intellectual leaders from complementary disciplines supported by other federal programs, international facilities, or in furtherance of their own FES funded research. Such interactions provide important indications of opportunities that could evolve into formal federal strategic partnerships.

For Vision 2025 to be accomplished, strategic federal and international partnerships need to be formed and maintained at a level that optimizes the execution of the Initiatives. For the FES Discovery Science subprogram, partnerships with other DOE offices or federal programs will be important in order for DPS scientists to access relevant existing or new machines in the furtherance of their research.

Transients Initiative

For this Initiative to be successful, it will be important for researchers to have access in the second half of the decade to long pulse tokamak devices such as EAST and KSTAR and,

[2] A "major upgrade" is defined as a significant capital project that required at least a one year downtime in user program operations. A "minimal" partnership corresponds to fewer than two scientist and engineer FTEs, "moderate" being between two and five FTEs, and "strong" greater than five FTEs

when operational, JT60-SA. The Panel views this as a mutually beneficial partnership in that research teams from EAST and KSTAR can be included in ELM and disruption research on short-pulse devices. The partnership between EAST and DIII-D appears to be mature, productive, and mutually beneficial. It will be important for FES to continue to support particularly the EAST partnership through maintenance of the appropriate partnership agreements. JT60-SA presents a particularly promising future partnership opportunity due to its size scale, and at the appropriate point in the decade, partnership agreements should be established as dictated by strategic need either for this Initiative or for the others.

Supporting Recommendation:

Develop a mutually beneficial partnership agreement with JT60-SA, similar to those already established on EAST and KSTAR, that will allow U.S. fusion researchers access to this larger-scale, long-pulse device in support of the report Initiatives.

The major challenges for Fusion Nuclear Science are to understand the ability of the first wall and divertor to accommodate reactor-level power and particle fluences while allowing the toroidal plasma to be controlled and sustained in a stationary, high pressure state. In addition, increasing research is needed to explore credible options for the structural materials, blanket and tritium production and extraction approaches for a long pulse fusion nuclear science facility that would be capable of high temperature (reactor relevant) operation at moderate duty cycles.

Strategic international partnerships are therefore required over the next decade to investigate key scientific issues, specifically collaborations that exploit the unique capabilities of superconducting long pulse tokamaks such as EAST, KSTAR, the JET-sized superconducting tokamak JT-60SA, which will start operation in 2019, and stellarators including LHD and W7-X. A partnership that exploits the divertor studies planned for the smaller-scale superconducting tokamak WEST could also be valuable for resolving critical scientific issues in PMI. Reference to these international facilities can be found in Appendix G.

As mentioned above, a highly collaborative relationship already exists with EAST that can be capitalized on for investigation of divertor issues and other PMI challenges. There is also a formal agreement between the U.S. and W7-X that will be valuable for developing PMI solutions. These partnerships will produce the critical data needed for the next step in designing a Fusion Nuclear Science Facility.

Experimentally Validated Integrated Predictive Capabilities Initiative

International partnerships also have an important role to play in this Initiative. Experiments conducted on international facilities that have the requisite diagnostic capability will provide the necessary data for model validation. Collaborations with international theorists through individual exchanges and through formal projects (such as verification exercises coordinated by the International Tokamak Physics Activity) will spur development of key modules. Ultimately, a mature predictive model can provide advance information needed to safely plan experiments on large international devices.

Fusion Nuclear Science Initiative

An important need for the success of the fusion nuclear science Initiative is the ability to understand the behavior of materials in an intense neutron field. To achieve that understanding, a new fusion materials neutron-irradiation facility that levers an existing MW-level neutron spallation source is envisioned as a highly cost-effective option. Such a facility exists in the BES program (Spallation Neutron Source). This rises to such high importance that the following partnership recommendation is made to FES.

Supporting Recommendation

Develop a mutually beneficial partnership with BES that would enable fusion materials scientists access to the Spallation Neutron Source for irradiation studies. Such a partnership will require frequent and effective FES-BES communication, strong FES project management that adheres to Office of Science Project Management best practices, and acceptable mitigation of operational risks.

Collaboration with ITER's test blanket module (TBM) program and JET for DT campaign is an important aspect of supporting the FNS Initiative by establishing the science and technology for blanket development, tritium breeding, extraction and fuel-cycle sustainability.

An area that has received little attention is the safety and associated regulations required to operate nuclear fusion devices. However, expertise exists in federal and international programs that FES can leverage to develop the appropriate regulatory approach. These programs include NE, NRC, IAEA, ITER, and JET.

Discovery Plasma Science

There are mutually beneficial, multi-agency partnership opportunities for DPS research activities. The expansion of such opportunities for FES to explore are between SC and NNSA, as well as across other federal agencies (e.g., NSF, NASA, DOD, NIST, EPA).

Within DOE SC, the highly productive Scientific Discovery through Advanced Computing (SciDAC) partnership is an example of strengths across all six SC offices. SciDAC partnerships between ASCR and FES are directed toward the development and application of computer simulation codes for advancing the science of magnetically confined plasmas. Predictive modeling codes have a pivotal role in all three thematic areas: BPS Foundation, BPS Long Pulse, and Discovery Plasma Science. In addition, there is the Matter at Extreme Conditions (MEC) end station of the Linac Coherent Light Source (LCLS) user facility at the SLAC National Accelerator Laboratory that serves as an example of a successful BES-FES partnership that provides users with access to HED regimes uniquely coupled with a high-brightness x-ray source.

Partnerships also exist within DPS across federal agencies. One is the NSF/DOE Partnership in Basic Plasma Science and Engineering that provides funding opportunities for small-group and single-investigator research activities unrelated to fusion. Although underfunded in the FY2015 President's Budget Request (Budget Scenario 4), there is also the NNSA-SC Joint Program in High Energy Density Laboratory Plasmas (HEDLP). Funding for that program was redirected into the DPS General Plasma Science area beginning in FY14. The NNSA component of the HEDLP partnership still remains as the

Stewardship Science Academic Alliances for academic research in the areas of materials under extreme conditions, low energy nuclear science, radiochemistry, and high energy density physics.

Although the description found in Appendix D of the NRC Plasma 2010 report "Federal Support for Plasma Science and Engineering" points out that plasma research across the various government agencies did not lend itself to a comprehensive view of federal investments, the report listed the following plasma research areas funded by agencies in addition to DOE SC:

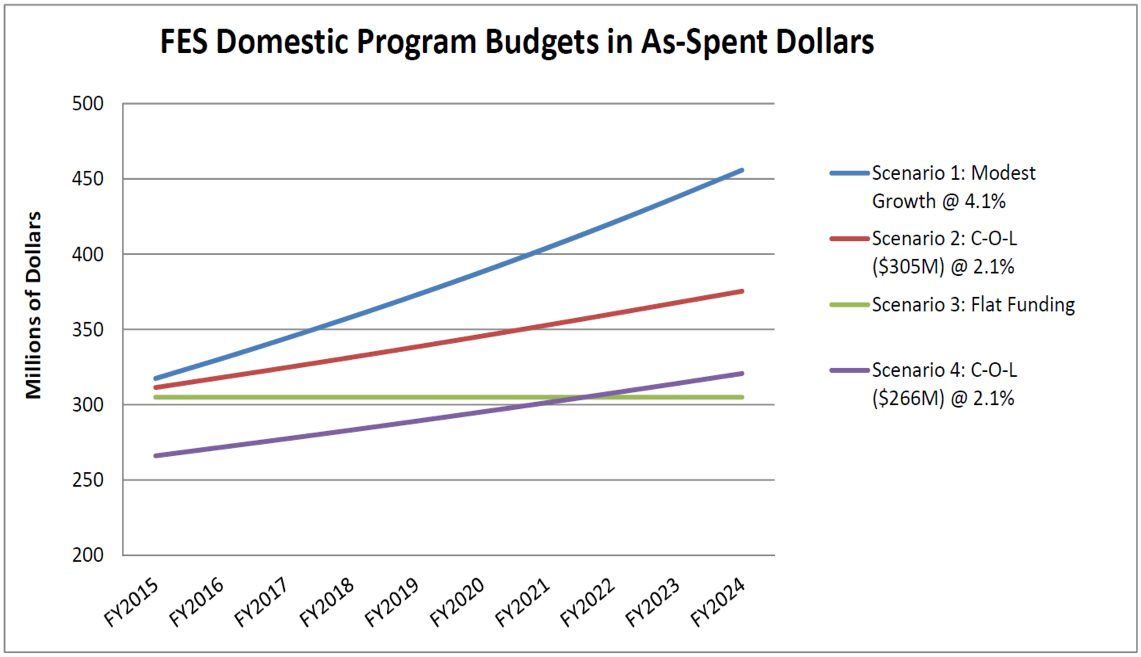
- NSF investments in low-temperature plasma science as well as space and astrophysical plasmas,
- NNSA as the primary funding agency for HED physics, and
- NASA support of space and astrophysical plasmas.

One partnership goal that might be fruitful would be in the area of mutually beneficial, intermediate-scale facilities for expanding into new plasma regimes (also discussed in the NRC Plasma 2010 report), with the option of co-funding for construction, operations, and the corresponding user research program.

Chapter 6. Budgetary considerations

Introduction

Here the Panel considers the actionable items recommended by this report, namely the four Initiatives, and how their implementation is tied to the four budget scenarios specified in the Charge. The Initiatives have been given short titles for convenience: Transients, Interfaces, Predictions, and Fusion Nuclear Science (FNS). The Initiatives are described in non-scientific terms in the Executive Summary, in integrated form and more detail in Chapter 1, and in scientific detail specific to either Foundations or Long Pulse in Chapters 2 and 3. The four budget scenarios are bounded on the high end by Budget Scenario 1 ($305M in FY14 with modest growth of 4.1% per year) and on the low end by Budget Scenario 4 (FY15 President's Budget Request of $266M with cost of living increase of 2.1% per year). Over the 10 years considered here, from FY15 through FY24, the total integrated amount between the two bounding cases differs by approximately $900 million.



The key question is how should the U.S. FES program be optimized under the different budget scenarios so that as much of Vision 2025 is achieved, as many of the four Initiatives are completed, and the U.S. fusion energy community maintains its leadership roles in as many areas as possible? The approach the Panel took for each budget scenario was to maximize the number of Initiatives undertaken within the constraints outlined below.

Facilities

Based on community input, the Long Pulse and Foundations subpanels estimated the requirements for each of their contributions to the four Initiatives. Two new experimental facilities and associated operations are implied. One, for the FNS Initiative, is a neutron-irradiation capability. The other, for the Interfaces Initiative, is a facility or facilities for investigating boundary plasma – materials interactions and their consequences. Cost considerations determined that this aspect of the Interfaces Initiative was best explored using an iterative process involving data from a new linear divertor simulator, data from one or more of NSTX-U and DIII-D with upgraded divertor(s), and results from modeling and simulation. The Panel expects that one U.S. facility for innovative boundary studies with advanced divertor scenarios will be upgraded during the latter half of the 10-year period. This effort will make use of the fundamental studies of plasma-materials interaction in the Long Pulse subprogram, and will transition to steady-state boundary research on long-pulse international superconducting tokamaks, also in the Long Pulse subprogram.

The Panel assumed the funding required for each of the four Initiatives would be obtained by reallocating funds from the budget category Foundations Operations, or from Discovery Plasma Science. Concerning the operation of the existing major tokamak facilities, the Panel reached the following decisions:

- Propose the immediate cessation of C-MOD. At the same time, the Panel agreed that the associated research funds would be maintained in full for research on other facilities, while the operations funding will be redirected to the proposed Initiatives. It is imperative for the U.S. Fusion Program that the knowledge, excellence, and leadership of the scientists from the MIT Plasma Science and Fusion Center be maintained and applied to the Initiatives to assure success.

Beyond the cessation of C-MOD, the Panel reached the following conclusions on facilities:

- Between ~ 2015 and ~2020, both NSTX-U and DIII-D should be available for ITER-related research, for assessing FNSF magnetic geometry (in particular NSTX-U), and for the Transients Initiative (in particular DIII-D). The Panel expects expanded and new international partnerships to develop.
- Between ~2020 and ~2025, at least one or the other of NSTX-U and DIII-D is required, including for ITER-related research, and for the Interfaces and Predictions Initiatives. The Panel expects new international partnerships on superconducting tokamaks and stellarators to flourish.
- After 2025, one facility is required both for a user facility for DPS and for programmatic fusion research. The best facility for the period beyond 2025 is not necessarily the same as the best facility for the 5 years prior to 2025. If this is the case, then cold storage, i.e., mothballing, should be considered.
- Between 2015 and 2025 the DPS program is strengthened by peer-reviewed university, national laboratory, and industry collaborations. These collaborations would be enhanced by federal partnerships involving cost sharing of collaborative, intermediate-scale facilities in order to realize the broadest range of plasma science discoveries. With such collaborations in place, the DPS program will be able to train the next generation of plasma scientists to ensure continuing U.S. leadership in plasma science.

Implementation

For each of the budget scenarios, it was assumed that the scientific workforce was retained in the event of a facility closure. In reallocating funds to the Initiatives there were obvious problems with time histories as facility closures result in sudden funding reductions and adoption of new Initiatives require a more gradual funding increase.

For the first 5 years (2015 to 2020) the number of run weeks of the two operating facilities (NSTX-U and DIII-D) should be kept high (significantly higher than in the recent past). Between 2020 and 2025, the number of facilities would be at least one, with the date of any shut down (or cold storage / mothball) being budget-dependent. In addition, if two facilities were maintained (perhaps possible only in Budget Scenario 1), the operational availability of one but not both could be reduced.

Findings

The Panel explored a variety of funding scenarios for the MFE-ReNeW Thrusts in order to derive credible funding profiles for the highest priority research activities. The combined expertise and experience of the panel members resulted in the following conclusions, organized by the highest to lowest budget scenarios. All dates are to be taken as approximate:

- Budget Scenario 1 - Modest growth of appropriated FY2014 ($305M) at 4.1%. This has the highest integrated funding. Vision 2025 has an acceptable probability of being achieved. Both NSTX-U and DIII-D facilities operate for 5 years, and possibly for 10 years (at reduced availability) with one upgraded divertor. If funding only one of the facilities is possible, it is not yet clear which is optimal. After 10 years only one facility is required, but it is not clear which one. All four Initiatives go forward, informing the design of FNSF. Both the divertor simulator and neutron-irradiation capability are providing data. The U.S. Fusion Program features prominently in four areas: Transients, Interfaces, Predictions, and, importantly, FNS.

- Budgets Scenario 2 - FY2014 with 2.1% cost of living. This has the second highest integrated funding, but at the end of FY2024 these integrated funds are approximately $400M less than in Budget Scenario 1. There is a lower probability that Vision 2025 can be met. One of the two remaining major tokamak facilities, DIII-D and NSTX-U, will be closed or mothballed between 2020 and 2025, and DPS funds may be affected. Only one major tokamak facility is required beyond 2025. All four Initiatives go forward, with three (Transients, Interface, Predictions) being emphasized. If necessary the Tier 2 Initiative FNS is slowed down. The U.S. Fusion Program features prominently in at least three Initiative areas (Transients, Interfaces, Predictions), with the possibility of featuring prominently in the FNS Initiative.

- Budget Scenario 3 - FY2014 flat. This has the third highest integrated funding, but at the end of FY2024 these integrated funds are approximately $780M less that the highest budget, Budget Scenario 1. Vision 2025 will be only partially met. One of the two remaining facilities, DIII-D and NSTX-U, will be closed or mothballed between 2020 and 2025, earlier than in the Budget Scenario 2, and DPS funds affected. Only one major tokamak facility will remain beyond 2025. The divertor simulator is scientifically productive. The two Tier 1 Initiatives (Transients, Interfaces) and one Tier 2 Initiative (Predictions) go forward, but the Tier 2 Initiative FNS is slowed. The U.S. Fusion Program features prominently in two, possibly three Initiative areas (Transients, Interfaces, Predictions).

- Scenario 4 - FY2015 request with 2.1% cost of living. Integrated funding over the 10 year period is approximately $900M less that Budget Scenario 1. Vision 2025 will be partially met, but a second Initiative is lost. However, the U.S. will maintain leadership encompassed by the two Tier-1 Initiatives, specifically Transients and Interfaces. The necessary delay to the Initiatives FNS and Predictive could allow international partners to take the leading role in these areas. The U.S. could feature prominently in two Initiative areas (Transients and Interfaces).

An additional consideration in the lower budget scenarios is how to best utilize any mid-year augmentation that might be appropriated in a single fiscal year. The answer depends on the amount of the augmentation. For a small one-time increase, priority should be given to making whole any reductions to the Tier 2 Initiative Predictions. For a larger increase, both Tier 2 Initiatives Prediction and FNS should be augmented. Any increase large enough to beneficially influence FNS would simultaneously extend benefits to the Predictions Initiative, which is less expensive overall than the FNS Initiative. The Panel concluded that, under the circumstances of an even larger one-time increase, building and operating the neutron-irradiation facility would be strategically important for exerting long-term world leadership in FNS.

Appendices

Appendix A: Summary of Initiatives and Recommendations

Each subpanel identified candidate initiatives, primary and supporting recommendations, and minimum funding requirements to meet Vision 2025.

For Foundations and Long Pulse, the prioritization was performed by considering the following set of metrics:

a. Importance – Necessity of the activity for ensuring that the U.S. is in a position to exert long-term leadership roles within the fusion energy mission as extrapolated from present knowledge.

b. Urgency – Necessity of the activity that is required immediately and in the near future.

c. Generality – Breadth of activity across FES subprograms and subprogram elements and necessity of the activity for resolving generic issues across different designs or approaches for ITER, FNSF, or DEMO, the demonstration fusion reactor facility.

d. Leadership Sustainment – Necessity of investment in order to sustain leading U.S. influence on progress of the field.

e. Leadership-Loss Mitigation – Necessity of investment in order to mitigate loss of U.S. leadership (short and long term) where the U.S. now leads.

f. Opportunity Reaching – Necessity of investment in order to turn a gap-opportunity pair into U.S. leadership for the long term.

g. ITER/FNS Need – Necessity of investment in order to address the need to establish the scientific basis for advancing fusion nuclear science.

h. Leverage and Partnering – Necessity of investment in order to strengthen or create a new partnership with other federal and international research programs that may foster important scientific opportunities otherwise unavailable to U.S. fusion scientists.

i. Efficiency – All criteria above, normalized by required magnitude of additional emphasis or investment.

For DPS, the prioritization was performed by considering the following set of metrics (further details in Chapter 4):

a. Advancing the frontiers of plasma innovation and plasma applications.
b. Forming collaborations between universities, national laboratories and industry, and across federal agencies.
c. Achieving cross cutting benefits to all FES subprograms, especially in training the next generation of plasma scientists.

The Partnership and Leverage subpanel prioritization was performed using the following four criteria (further details are in Chapter 5):

a. Importance and urgency consistent with Vision 2025;
b. Return on FES investment;

c. Sustained & expanded U.S. leadership; and
d. Clear mutual benefit.

The Panel integrated and iterated these findings, resulting in four high priority Initiatives that could be accommodated over ten years under a majority of the budget scenarios. These Initiatives were further ranked into upper and lower tiers, with an understanding that those in the lower tier would be delayed under the lower budget scenarios.

2025 Vision: (1) Enable successful operation of ITER with a significant leading participation by the U.S. (2) Provide the scientific basis for a U.S. Fusion Nuclear Science Facility (FNSF) and (3) Create a U.S. "Generation ITER-FNSF" workforce that is leading scientific discoveries and technological innovation.

Tier 1 Initiatives:	Four Primary Recommendations	BPS Foundations Supporting Recommendations	BPS Long Pulse Supporting Recommendations	Partnerships Supporting Recommendations
Control deleterious transient events in burning plasmas: Undesirable transients in tokamak plasmas are ubiquitous but tolerable occurrences in most present-day experiments, but some events could prove too limiting to regular operation of an experiment without frequent shutdowns for repairs. To either avoid these or negate their consequences, both passive and active control techniques, as well as preemptive plasma-shut-down measures, will be employed.	Control of Burning Plasmas: The FES experimental program needs an integrated and prioritized approach to achieve significant leading participation by the U.S. on ITER. Specifically, new proposed solutions will be applied to two long-standing and ubiquitous show-stopping issues, relevant for tokamak-based burning fusion plasmas. The issues are: (1) dealing with unwanted transients, and (2) dealing the interaction between the plasma boundary and material walls.	Supporting Recommendation: Maintain the strong experimental U.S. focus on eliminating and/or mitigating destructive transient events to enable the high-performance operation of ITER. Develop improved predictive modeling of plasma behavior during controlled transient events to explore the basis for the disruption-free sustained tokamak scenario for FNSF and DEMO.		Supporting Recommendation: Develop a mutually beneficial partnership agreement with JT60-SA, similar to those already established on EAST and KSTAR, that will allow U.S. fusion researchers access to this larger-scale, long-pulse device in support of the Report's Initiatives.
Taming the plasma-material interface: The critically important boundary region of a fusion plasma involves the transition from the high-temperature plasma core to the surrounding material. Understanding the specific properties of this boundary region that determine the overall plasma confinement is a priority. At the same time, the properties of this boundary region control the heat and particle fluxes incident on material surface. The response of the material surfaces influences the boundary region itself. Understanding, accommodating, and controlling this complex interaction, including materials selection to withstand this harsh environment while maintaining high confinement, is a prerequisite for ITER success and for designing FNSF. The panel concluded that the most cost-effective path to a self-consistent solution requires the construction of a prototypic high-power and high-fluence linear divertor simulator. Results from this facility will be iterated with experimental results on suitably equipped domestic and international tokamaks and stellarators, as well as in numerical simulations.		Supporting Recommendation: Undertake a technical assessment with community experts to ascertain which existing facility could most effectively address the key boundary physics issues.	Supporting Recommendation: To design and build an advanced multi-effects linear divertor simulator to support the Interface initiative.	
Tier 2 Initiatives:				
Experimentally Validated Integrated Predictive Capabilities: The coming decade provides an opportunity to break ground in integrated predictive understanding that is urgently required as the ITER era begins and plan are developed for the next generation of facilities. Traditionally, plasma theory and simulation provide models for isolated phenomena based on mathematical formulations that have restricted validity regimes. However, there are crucial situations where the coupling between the validity regime and the phenomena is required, which implies that new phenomena can appear. To understand and predict these situations requires expanded computing capabilities strongly coupled to enhancements in analytic theory and the use of applied mathematics. This effort must be strongly connected to a spectrum of plasma experimental facilities supported by a vigorous diagnostics subprogram in order to provide crucial tests of theory and allow for validation.	Fusion Predictive Modeling: The FES theory and simulation subprogram should develop the modeling capability to understand, predict, and control (a) burning, long pulse fusion plasmas and (b) plasma facing components. Such a capability when combined with experimental operational experience will maximize the U.S. operation and interpretation of ITER results for long pulse, burning plasmas, and decide the necessary requirements for future fusion facilities. This endeavor must encompass the regions from plasma core through to the edge and into the surrounding materials, and requires coupling nonlinear, multi-scale, multi-disciplinary phenomena, in experimentally validated, theoretically based models.	Supporting Recommendation: Maintain and strengthen existing base theory and SCIDAC subprograms to maintain world leadership and leverage activities with the broader applied mathematics and computer science communities Supporting Recommendation: Ensure excellence in the Experimentally Validated Integrated Predictive Capabilities Initiative with a peer-reviewed, competitive proposal process. A community-wide process is needed to precisely define the scope and implementation strategy for ultimately realizing a whole-device predictive model.		
Fusion Nuclear Science: Several important near-term decisions will shape the pathway toward practical fusion energy. The selection of the plasma magnetic configuration (an advanced tokamak, spherical torus, or stellarator) and plasma operational regimes needs to be established based on focused domestic and international collaborative long-pulse, high-power research. Another need is the identification of a viable approach to a robust plasma-materials interface that provides acceptably high heat flux capability and low net erosion rates without impairing plasma performance or tritium entrapment. Materials science research needs to be expanded to comprehend and mitigate fusion neutron-irradiation effects and fundamental research is needed to identify a feasible tritium fuel-cycle and power-conversion concept. A new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source is envisioned as a highly cost-effective option.	Fusion Nuclear Science: A fusion nuclear science subprogram should be created to provide the science and technology understanding for informing decisions on the preferred plasma confinement, materials, and tritium fuel-cycle concepts for a Fusion Nuclear Science Facility (FNSF), a proposed U.S.-based international centerpiece beyond 2025. FNSF's mission is to utilize an experimental long-pulse (up to one million second duration) plasma platform for the convergence and complex integration of fusion plasma science and fusion nuclear science.		Supporting Recommendation: To design and build a new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source to support the Fusion Nuclear Sciences Initiative. Supporting Recommendation: To invest in a research subprogram element on blanket technologies and tritium sustainability that will advance studies from single to multiple effects and interactions.	Supporting Recommendation: Develop a mutually beneficial partnership with BES that would enable fusion materials scientist access to the Spallation Neutron Source for irradiation studies. Such a partnership will require frequent and effective FES-BES communication, strong FES project management that adheres to Office of Science Project Management best practices, and acceptable mitigation of operational risks.
		Discovery Plasma Science (DPS) Supporting Recommendations for GPS, HEDLP, SO-systems, and Diagnostic Innovation		
In concert with the above Initiatives, Discovery Plasma Science will advance the frontiers of plasma knowledge to continue U.S. leadership.	Discovery Plasma Science: FES stewardship of basic plasma research should be accomplished through strengthening of peer-reviewed university, national laboratory, and industry collaborations. In order to realize the broadest range of plasma science discoveries, the research should be enhanced through federal-agency partnerships that include cost-sharing of intermediate-scale collaborative facilities.	DPS General Plasma Science Supporting Recommendation: FES should take the lead for exploring multi-agency partnering for GPS activities. This effort should include funding for intermediate-scale facilities (as discussed in the NRC Plasma 2010 report) with funding for construction, operations, facility-staff research, and the corresponding user-research program. DPS HEDLP Supporting Recommendation: FES should avail itself of levering opportunities at both SC and NNSA high-energy-density-physics user facilities, within the context of the NNSA-SC Joint Program in HEDLP, especially for the FES HEDLP community researchers who have been awarded experimental shot time. DPS Self-Organized Systems Supporting Recommendation: FES should manage the elements of SO-Systems using subprogram-wide metrics with peer reviews occurring every 3 to 5 years to provide a suite of capabilities that is more than sum of the individual parts and that explore a broader set scientific questions. DPS Diagnostic Measurement Innovations Supporting Recommendation: FES should manage diagnostic development and measurement innovation to have a coordinated cross-cutting set of predictive model validation activities across all DPS subprogram elements: GPS, HEDLP, and SO-Systems.		

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Tier 1 Initiatives:	Four Primary Recommendations	BPS Foundations Supporting Recommendations	BPS Long Pulse Supporting Recommendations	Partnerships Supporting Recommendations
Control deleterious transient events in burning plasmas: Undesirable transients in tokamak plasmas are ubiquitous but tolerable occurrences in most present-day experiments, but some events could prove too limiting to regular operation of an experiment without frequent shutdown for repairs. To either avoid these or negate their consequences, both passive and active control techniques, as well as preemptive plasma-shut-down measures, will be employed.	Control of Burning Plasmas: The FES experimental program needs an integrated and prioritized approach to achieve significant leading participation by the U.S. on ITER. Specifically, new proposed solutions will be applied to two long-standing and ubiquitous show-stopping issues, relevant for tokamak-based burning fusion plasma. The issues are: (1) dealing with unwanted transients, and (2) dealing the interaction between the plasma boundary and material walls.	Supporting Recommendation: Maintain the strong experimental U.S. focus on eliminating and/or mitigating destructive transient events to enable the high-performance operation of ITER. Develop improved predictive modeling of plasma behavior during controlled transient events to explore the basis for the disruption-free sustained tokamak scenario for FNSF and DEMO.		Supporting Recommendation: Develop a mutually beneficial partnership agreement with JT60-SA, similar to those already established on EAST and KSTAR, that will allow U.S. fusion researchers access to this larger-scale, long-pulse device in support of the Report's Initiatives.
Taming the plasma-material interface: The critically important boundary region of a fusion plasma involves the transition from the high-temperature plasma core to the surrounding material. Understanding the specific properties of this boundary region that determine the overall plasma confinement is a priority. At the same time, the properties of this boundary region control the heat and particle fluxes incident on material surface. The response of the material surfaces influences the boundary region itself. Understanding, accommodating, and controlling this complex interaction, including materials selection to withstand this harsh environment while maintaining high confinement, is a prerequisite for ITER success and for designing FNSF. The panel concluded that the most cost-effective path to a self-consistent solution requires the construction of a prototypic high-power and high-fluence linear divertor simulator. Results from this facility will be iterated with experimental results on suitably equipped domestic and international tokamaks and stellarators, as well as in numerical simulations.		Supporting Recommendation: Undertake a technical assessment with community experts to ascertain which existing facility could most effectively address the key boundary physics issues.	Supporting Recommendation: To design and build an advanced multi-effects linear divertor simulator to support the Interface Initiative.	
Tier 2 Initiatives:				
Experimentally Validated Integrated Predictive Capabilities: The coming decade provides an opportunity to break ground in integrated predictive understanding that is urgently required as the ITER era begins and plan are developed for the next generation of facilities. Traditionally, plasma theory and simulation provide models for isolated phenomena based on mathematical formulations that have restricted validity regimes. However, there are crucial situations where the coupling between the validity regime and the phenomena is required, which implies that new phenomena can appear. To understand and predict these situations requires expanded computing capabilities strongly coupled to enhancements in analytic theory and the use of applied mathematics. This effort must be strongly connected to a spectrum of plasma experimental facilities supported by a vigorous diagnostics subprogram in order to provide crucial tests of theory and allow for validation.	Fusion Predictive Modeling: The FES theory and simulation subprogram should develop the modeling capability to understand, predict, and control (a) burning, long pulse fusion plasmas and (b) plasma facing components. Such a capability when combined with experimental operational experience will maximize the U.S. operation and interpretation of ITER results for long pulse, burning plasmas, and decide the necessary requirements for future fusion facilities. This endeavor must encompass the regions from plasma core through to the edge and into the surrounding materials, and requires coupling nonlinear, multi-scale, multi-disciplinary phenomena, in experimentally validated, theoretically based models.	Supporting Recommendation: Maintain and strengthen existing base theory and SCIDAC subprograms to maintain world leadership and leverage activities with the broader applied mathematics and computer science communities. Supporting Recommendation: Ensure excellence in the Experimentally Validated Integrated Predictive Capabilities Initiative with a peer-reviewed, competitive proposal process. A community-wide process is needed to precisely define the scope and implementation strategy for ultimately realizing a whole-device predictive model.		
Fusion Nuclear Science: Several important near-term decisions will shape the pathway toward practical fusion energy. The selection of the plasma magnetic configuration (an advanced tokamak, spherical torus, or stellarator) and plasma operational regimes needs to be established based on focused domestic and international collaborative long-pulse, high-power research. Another need is the identification of a viable approach to a robust plasma-materials interface that provides acceptably high heat flux capability and low net erosion rates without impairing plasma performance or tritium entrapment. Materials science research needs to be expanded to comprehend and mitigate fusion neutron-irradiation effects and fundamental research is needed to identify a feasible tritium fuel-cycle and power-conversion concept. A new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source is envisioned as a highly cost-effective option.	Fusion Nuclear Science: A fusion nuclear science subprogram should be created to provide the science and technology understanding for informing decisions on the preferred plasma confinement, materials, and tritium fuel-cycle concepts for a Fusion Nuclear Science Facility (FNSF), a proposed U.S.-based international centerpiece beyond 2025. FNSF's mission is to utilize an experimental long-pulse (up to one million second duration) plasma platform for the convergence and complex integration of fusion plasma science and fusion nuclear science.		Supporting Recommendation: To design and build a new fusion materials neutron-irradiation facility that leverages an existing MW-level neutron spallation source to support the Fusion Nuclear Sciences Initiative. Supporting Recommendation: To invest in a research subprogram element on blanket technologies and tritium sustainability that will advance studies from single to multiple effects and interactions.	Supporting Recommendation: Develop a mutually beneficial partnership with BES that would enable fusion materials scientist access to the Spallation Neutron Source for irradiation studies. Such a partnership will require frequent and effective FES-BES communication, strong FES project management that adheres to Office of Science Project Management best practices, and acceptable mitigation of operational risks.
		Discovery Plasma Science (DPS) Supporting Recommendations for GPS, HEDLP, SO-systems, and Diagnostic Innovation		
In concert with the above Initiatives, Discovery Plasma Science will advance the frontiers of plasma knowledge to continue U.S. leadership.	Discovery Plasma Science: FES stewardship of basic plasma research should be accomplished through strengthening of peer-reviewed university, national laboratory, and industry collaborations. In order to realize the broadest range of plasma science discoveries, the research should be enhanced through federal-agency partnerships that include cost-sharing of intermediate-scale collaborative facilities.	DPS General Plasma Science Supporting Recommendation: FES should take the lead for exploring multi-agency partnering for GPS activities. This effort should include funding for intermediate-scale facilities (as discussed in the NRC Plasma 2010 report) with funding for construction, operations, facility-staff research, and the corresponding user-research program. DPS HEDLP Supporting Recommendation: FES should avail itself of levering opportunities at both SC and NNSA high-energy-density-physics user facilities, within the context of the NNSA-SC Joint Program in HEDLP, especially for the FES HEDLP community researchers who have been awarded experimental shot time. DPS Self-Organized Systems Supporting Recommendation: FES should manage the elements of SO-Systems using subprogram-wide metrics with peer reviews occurring every 3 to 5 years to provide a suite of capabilities that is more than sum of the individual parts and that explore a broader set scientific questions. DPS Diagnostic Measurement Innovations Supporting Recommendation: FES should manage diagnostic development and measurement innovation to have a coordinated		

Appendix B: Charge Letter

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

April 8, 2014

Professor Mark Koepke
Chair
Fusion Energy Sciences Advisory Committee
Department of Physics – White Hall 203
West Virginia University
1315 Willey Street
Morgantown, WV 26506

Dear Professor Koepke:

First, let me thank you for accepting the task of chairing the Fusion Energy Sciences Advisory Committee (FESAC) at this important time for the Fusion Energy Sciences (FES) program. We have considerable work ahead that will require thoughtful, informed advice regarding the future of fusion and plasma sciences in the United States.

The FY 2014 Omnibus Appropriations Act requires the Department to submit a strategic plan for the FES program by January 2015 with the following guidance:

> "The ten-year plan should assume U.S. participation in ITER and assess priorities for the domestic fusion program based on three funding scenarios with the fiscal year 2014 enacted level as the funding baseline: (1) modest growth, (2) budget growth based only on a cost-of-living-adjusted fiscal year 2014 budget, and (3) flat funding. The January 2013 Nuclear Science Advisory Committee report on priorities for nuclear physics used similar funding scenarios and should serve as a model for assessing priorities for the fusion program."

Based on this direction, we are asking FESAC to address the following three scenarios with the FY 2014 appropriation for the domestic program as the baseline ($305M):

(1) Modest growth (use +2.0 percentage points above the published OMB inflators for FY 2015 through FY 2024)

(2) Cost of living (use the published OMB inflators for FY 2015 through FY 2024)

(3) Flat funding

We are also asking FESAC to consider a fourth scenario with the FY 2015 President's Request for the domestic program as the baseline ($266M):

(4) Cost of living (use the published OMB inflators for FY 2015 through FY 2024)

We ask FESAC to assess the priorities among continuing and potential new FES program investments required to ensure that the U.S. is in a position to exert long term leadership roles within and among each of the following areas:

- Burning Plasma Science: Foundations – the science of prediction and control of burning plasmas ranging from the strongly driven to the self-heated state;
- Burning Plasma Science: Long Pulse – the science of fusion plasmas and materials approaching and beyond ITER-relevant heat fluxes, neutron fluences, and pulse lengths;
- Discovery Plasma Science – the study of laboratory plasmas and the high energy density state relevant to astrophysical phenomena, the development of advanced measurement for validation, and the science of plasma control important to industrial applications.

You are to prioritize between the program elements defined for you by FES; your report may also include your views on new facilities, new research initiatives, and facility closures. FES interest in the study of driven as well as self-heated burning plasmas is motivated by the need to establish the scientific basis for advancing fusion nuclear science. Include in your report an assessment of the potential for strengthened or new partnerships with other federal and international research programs that may foster important scientific opportunities otherwise unavailable to U.S. fusion scientists. These may include partnerships to enable research in equilibrium sustainment of long pulses (hundreds of seconds and more), fusion neutron materials science, and multi-scale computing.

Your subcommittee should make use of prior studies. For example, the FESAC report, "Priorities, Gaps, and Opportunities," issued in 2007, identified gaps in the world's magnetic confinement fusion research program and potential initiatives the U.S. might undertake to assert leadership in select areas. The 2009 report, "Research Needs for Magnetic Fusion Energy Sciences," built on this analysis. In the area of Discovery Plasma Science, the National Academies undertook a decadal study of the field (2007), and identified research needs and opportunities for the U.S. to extend its leadership in this class of research. Since that time there have been other FESAC studies identifying research needs in the plasma sciences, in materials research, and also regarding international research opportunities.

Your report will be used as the Office of Science develops a FES strategic plan for submission to Congress by the January 2015 deadline. I therefore request that you submit your report to me by October 1, 2014.

Sincerely,

Patricia M. Dehmer

Patricia M. Dehmer
Acting Director, Office of Science

Appendix C: Panel Roster

Kevin Bowers: Los Alamos National Laboratory (guest scientist)
Troy Carter: University of California – Los Angeles
Don Correll: Lawrence Livermore National Laboratory
Arati Dasgupta: Naval Research Laboratory
Chris Hegna: University of Wisconsin – Madison
William "Bill" Heidbrink: Univ. California – Irvine
Stephen Knowlton: Auburn University (retired)
Mark Koepke: *Panel Chair*: West Virginia University
Douglas Kothe: Oak Ridge National Laboratory
Stan Milora: Oak Ridge National Lab (retired)
David E. Newman: University of Alaska
Gert Patello: Pacific Northwest National Laboratory
Don Rej: Los Alamos National Laboratory
Susana Reyes: Lawrence Livermore National Laboratory
John Steadman: University of South Alabama
Karl A. Van Bibber: University of California – Berkeley
Alan Wootton: University of Texas-Austin (retired)
Minami Yoda: Georgia Institute of Technology
Steve Zinkle: *Panel Vice Chair*: University of Tennessee - Knoxville

Appendix D: Panel Process and Meetings

Week 1 (14-18 April): Finalize SP panel membership, initiate invitation process
Week 3 (28 April – 2 May): **1st SP Teleconference**: Plans for Process and Gathering Input
Week 6 (19-23 May): **2nd SP Telecon**: Gathered Input – relevant reports
Week 8 (2-6 June): **1st SP Meeting** – Mon 1830 to Friday 1330 with 3-days of talks
Week 13 (7-11 July): **2nd SP Meeting** – Mon 0900 to Friday 1330 with 3-days of talks
Week 19 (18-22 August): **3rd SP Telecon**: Priority Assessment
Week 20 (25-29 August): **4th SP Telecon**: Budget Scenarios
Week 21 (2-5 September): **3rd SP Meeting** – Tues 1830 to Friday 1700 with no talks
Week 24 (22-26 September): Monday, Tuesday, **FESAC SP Panel Report Approval Meeting**

Appendix E: Community White Papers received for Status and Priorities, and Initiatives

Author(s)	Title or Subject
Mohamed Abdou, Alice Ying, Sergey Smolentsev, and Neil B. Morley of UCLA	Scientific Framework for Advancing Blanket/FW/Tritium Fuel Cycle Systems towards FNSF & DEMO Readiness – Input to FESAC Strategic Plan Panel on Blanket/FW Research Initiatives
Ed Barnat, Sandia National Laboratories, Albuquerque N.M.	Dynamic exploratory clusters: Facilitating inter-disciplinary discovery driven research
L.R. Baylor, G.L. Bell, T. S. Bigelow, J. B. Caughman, R. H. Goulding, G.R. Hanson, and D.A. Rasmussen, ORNL, J. C. Hosea, G. Taylor, and R. Perkins, PPPL, J. M. Lohr, P. B. Parks, and R. I. Pinsker, GA, G. Nusinovich, U. of Maryland, M. A. Shapiro and R. J. Temkin, MIT	Plasma Controlling and Actuation Technologies that Enable Long Pulse Burning Plasma Science – Status and Priorities

R. Boivin (GA), M. Austin (UT), T. Biewer (ORNL), D. Brower (UCLA), E. Doyle (UCLA), G. McKee (UW), P. Snyder (GA)	Enhanced Validation of Performance-Defining Physics through Measurement Innovation
Dylan Brennan, President, UFA, Phil Ferguson, ORNL, Raymond Fonck, UWISC, Miklos Porkolab, MIT, Stewart Prager, PPPL, Ned Sauthoff US ITER, Tony Taylor, GA	Perspectives on Ten-Year Planning for the Fusion Energy Sciences Program
USBPO Diagnostics Topical Group: David L. Brower, Leader. Theodore M. Biewer, Deputy, with R. Boivin, R. Moyer, C. Skinner, D. Thomas, K. Tritz, and K. Young	A Burning Plasma Diagnostic Initiative for the US Magnetic Fusion Energy Science Program
M. R. Brown, representing P. M. Bellan, S. A. Cohen, D. Hwang, E. V. Belova. Swarthmore College	The role of compact torus research in fusion energy science
Tom Brown, PPPL, A Personal View	U.S. Next Step Strategy for Magnetic Fusion
C. Denise Caldwell, NSF MPS-PHY	NSF'S Plasma Physics Program
R.W. Callis, A. Garofalo, V. Chan, H. Guo, GA	Applied Scientific Research to Prepare the Technology for Blanket and Nuclear Components to Enable Design of the Next-Step Burning Plasma Device (Status)
R.W. Callis, A. Garofalo, V. Chan, H. Guo, GA	Applied Scientific Research to Prepare the Technology for Blanket and Nuclear Components to Enable Design of the Next-Step Burning Plasma Device (Initiative)
C.S. Chang, Princeton Plasma Physics Laboratory	First-Principles Simulation of the Whole Fusion Physics on Leadership Class Computers, in collaboration with ASCR scientists
B. Coppi, MIT Physics	The High Field Compact Line of Experiment: From Alcator to Ignitor and Beyond
R Paul Drake, University of Michigan	Opportunities and Challenges in High-Energy-Density Laboratory Plasmas
R Paul Drake, University of Michigan	Initiatives in High-Energy-Density Laboratory Plasmas
Philip C. Efthimion, PPPL	OFES Stewardship of Plasma Science and its Partnering and Leveraging Discovery Science
R. Fonck, UWISC, G. McKee, GA, D. Smith, PPPL	Revitalizing university and national facility integration in Fusion Energy Science
W. Fox, A. Bhattacharjee, H. Ji, K. Hill, I. Kaganovich, and R. Davidson, PPPL, A. Spitkovsky, Princeton U., D.D. Meyerhofer, R.	Laboratory astrophysics and basic plasma physics with high-energy-density, laser-produced plasmas

Betti, D. Froula, and P. Nilson, U. Rochester, D. Uzdensky and C. Kuranz, UMICH, R. Petrasso and C.K. Li, MIT PSFC, S. Glenzer, SLAC	
E. Fredrickson, PPPL	Some Recent Advances in Understanding of Energetic Particle Driven Instabilities and Fast-ion Confinement.
Andrea M. Garofalo and Tony S. Taylor, GA	Leveraging International Collaborations to Accelerate Development of the Fusion Nuclear Science Facility (FNSF)
S. H. Glenzer, SLAC National Accelerator Laboratory	US leadership in Discovery Plasma & Fusion Science
R. Goldston, PPPL, B. LaBombard, D. Whyte, M. Zarnstorff, MIT PSFC	A Strategy for Resolving the Problems of Plasma-Material Interaction for FNSF
C.M. Greenfield for the U.S. Burning Plasma Organization	Positioning the U.S. to Play a Leading Role in and Benefit from a Successful ITER Research Program
Martin Greenwald, a personal view	Implications and Lessons from 2007 Strategic Planning Activity and Subsequent Events
H.Y. Guo, E.A. Unterberg, S.L. Allen, D.N. Hill, A.W. Leonard, P.C. Stangeby, D.M. Thomas and DIII-D BPMIC Team	Developing Heat Flux and Advanced Material Solutions for Next-Step Fusion Devices
W. Guttenfelder, E. Belova, N.N. Gorelenkov, S.M. Kaye, J.E. Menard, M. Podesta, Y. Ren, and W.X. Wang, PPPL, D.L. Brower, N. Crocker, W.A. Peebles, T.L. Rhodes, and L. Schmitz, UCLA, J. Candy, G.M. Staebler, and R.E. Waltz, GA, J. Hillesheim, CCFE, C. Holland, UCSD, J.H. Irby and A.E. White, MIT, J.E. Kinsey, CompX, F.M. Levinton and H. Yuh, Nova Photonics, M.J. Pueschel, UWisc	Validating electromagnetic turbulence and transport effects for burning plasmas
G.W. Hammett, PPPL, with input from C.S. Chang, S. Kaye, and A. H. Hakim, PPPL, A. Pletzer and J. Cary, Tech-X	An Advanced Computing Initiative To Study Methods of Improving Fusion
R. J. Hawryluk PPPL, H. Berk UTEXAS, B. Breizman, UTEXAS, D. Darrow, PPPL, R. Granetz, MIT, D. Hillis, ORNL, A. Kritz, LEHIGH, G. Navrati, COLUMBIA U., T. Rafiq, LEHIGH, S. Sabbagh, COLUMBIA U, G. Wurden, LANL, and M. C. Zarnstorff, PPPL	US Collaboration on JET D-T Experiments
David N. Hill, LLNL	Develop the basis for PMI solutions for FNSF and DEMO
Matthew M. Hopkins, Sandia National Laboratories	Overcoming Cultural Challenges to Increasing Reliance on Predictive Simulation

W. Horton, H. L. Berk, C. Michoski, and D. Meyerson, UTEXAS Austin, I. Alvarado and L. Wenzel, National Instruments, Austin, Texas, A. Molvik, D. Ryutov, T. Simonen, and B. Hooper, LLNL, J. F. Santarius, UWISC	A Fusion Science Facility to Evaluate Materials for Fusion Reactors
P. W. Humrickhouse, M. Shimada, B. J. Merrill, L. C. Cadwallader, and C. N. Taylor, Idaho National Laboratory	Tritium research needs in support of long-pulse burning plasmas: gaps, status, and priorities
P. W. Humrickhouse, M. Shimada, B. J. Merrill, L. C. Cadwallader, and C. N. Taylor, Idaho National Laboratory	Tritium research needs in support of long-pulse burning plasmas: new initiatives
T. R. Jarboe, C. J. Hansen, A. C. Hossack, G. J. Marklin, K. D. Morgan, B. A. Nelson, D. A. Sutherland, and B. S. Victor	Helicity Injected Torus (HIT) Current Drive Program
Thomas R. Jarboe PI, Richard Milroy Co-PI, Brian Nelson Co-PI, and Uri Shumlak Co-PI, University of Washington, Carl Sovinec PI, University of Wisconsin, Eric Held, Utah State, Vyacheslav Lukin, NRL	Plasma Science and Innovation Center (PSI-Center) at Washington, Wisconsin, Utah State, and NRL
T. R. Jarboe, C. J. Hansen, A. C. Hossack, G. J. Marklin, K. D. Morgan, B. A. Nelson, R. Raman, D. A. Sutherland, B. S. Victor, and S. You	An Imposed Dynamo Current Drive experiment: studying and developing efficient current drive with sufficient confinement at high temperature
For SCIDAC: S. Jardin, PPPL, N. Ferraro, GA, A. Glasser, UWash, V. Izzo, UCSD, S. Kruger TechX, C. Sovinec, HRS Fusion, H. Strauss, UWISC	Increased Understanding and Predictive Modeling of Tokamak Disruptions
H. Ji for the WOPA Team	Initiative for Major Opportunities in Plasma Astrophysics in Discovery Plasma Science in Fusion Energy Sciences
H. Ji, PPPL, C. Forest, UWISC, M. Mauel, Columbia U., S. Prager, PPPL, J. Sarff, PPPL, and E. Thomas, Auburn U.	Initiative for a New Program Component for Intermediate-scale Experiments in Discovery Plasma Science in Fusion Energy Sciences
C. E. Kessel, P. W. Humrickhouse, N. Morley, S. Smolentsev, M. E. Rensink, T. D. Rognlien	Critical Fusion Nuclear Material Science Activities Required Over the Next Decade to Establish the Scientific Basis for a Fusion Nuclear Science Facility
C. E. Kessel, J. P. Blanchard, A. Davis, L. El-Guebaly, N. Ghoniem, P. W. Humrickhouse, A. Khodak, S. Malang, B. Merrill, N. Morley, G. H. Neilson, F. M. Poli, M. E. Rensink, T. D. Rognlien, A. Rowcliffe, S. Smolentsev, L. Snead, M. S. Tillack, P. Titus, L. Waganer, A. Ying, K. Young, Y. Zhai	Critical Fusion Nuclear Material Science Activities Required Over the Next Decade to Establish the Scientific Basis for a Fusion Nuclear Science Facility
Mike Kotschenreuther, Swadesh Mahajan, Prashant Valanju, Brent Covele, and Francois	Taming the Heat Flux Problem, Advanced Divertors towards Fusion

Waelbroeck, IFS, University of Texas; Steve Cowley UKAEA, John Canik ORNL, Brian LaBombard MIT, Houyang Guo, GA	Power
Predrag Krstić, Institute for Advanced Computational Science, SBU, Igor Kaganovich, Daren Stotler, Bruce Koel, PPPL	Priorities: Integrated Multi-Scale Divertor Simulation Project
Predrag Krstić, Institute for Advanced Computational Science, SBU, Igor Kaganovich, Daren Stotler, Bruce Koel PPPL	Initiatives: Integrated Multi-Scale Divertor Simulation Project
Mark J. Kushner, UMICH, EECS, Co-submitted by 28 other scientists, at 22 other locations	A Low Temperature Plasma Science Program: Discovery Science for Societal Benefit
Brian LaBombard, MIT PSFC	High priority divertor and PMI research on the pathway to FNSF/DEMO.
B. LaBombard, E. Marmar, J. Irby, J. Terry, R. Vieira, D.G. Whyte, S. Wolfe, S. Wukitch, N. Asakura, W. Beck, P. Bonoli, D. Brower, J. Doody, L. Delgado-Aparicio, R. Ellis, D. Ernst, C. Fiore, R. Granetz, M. Greenwald, Z.S. Hartwig, A. Hubbard, J.W. Hughes, I.H. Hutchinson, C. Kessel, M. Kotschenreuther, S. Krasheninnikov, R. Leccacorvi, Y. Lin, B. Lipschultz, S. Mahajan, J. Minervini, R. Nygren, R. Parker, F. Poli, M. Porkolab, M.L. Reinke, J. Rice, T. Rognlien, W. Rowan, D. Ryutov, S. Scott, S. Shiraiwa, D. Terry, C. Theiler, P. Titus, G. Tynan, M. Umansky, P. Valanju, F. Waelbroeck, G. Wallace, A. White, J.R. Wilson, S.J. Zweben	ADX: a high field, high power density advanced divertor tokamak experiment. Mission: Develop and demonstrate plasma exhaust and PMI physics solutions that scale to long pulse at FNSF/DEMO divertor parameters.
T.C. Luce, R.J. Buttery, C.C. Petty, M.R. Wade, GA	Preparing the Foundations for Burning Plasmas and Steady-state Tokamak Operation
T.C. Luce, GA	Missions and Priorities for the US Fusion Program—the Role of Burning Plasma and Steady-State Tokamak Physics
N.C. Luhmann, Jr., A.V. Pham (UC Davis), T. Munsat (U. Colorado)	Advanced Electronics Development for Fusion Diagnostics
R. Maingi, M.A. Jaworski, R. Kaita, R. Majeski, C.H. Skinner, and D.P. Stotler, PPPL, J.P. Allain, D. Andruczyk, D. Currelli, and D.N. Ruzic, Princeton University, B.E. Koel, UIUC	A Liquid Metal PFC Initiative
E. S. Marmar, on behalf of the MIT Alcator Team	Priorities and Opportunities, White Paper for MIT/PSFC 10 Year Research Plan
E. S. Marmar, on behalf of the MIT Alcator Team	Initiatives led by the MIT Plasma Science and Fusion Center: Successful Completion of Alcator C-Mod and

	Transition to a New, Advanced Divertor High-Field Tokamak Facility
M. Mauel, D. Garnier, J. Kesner, P. Michael, M. Porkolab, T. Roberts, P. Woskov, Dept of Applied Physics and Applied Math, Columbia U., MIT PSFC	Multi-University Research to Advance Discovery Fusion Energy Science using a Superconducting Laboratory Magnetosphere
J. Menard, R. Fonck, R. Majeski for the NSTX-U, Pegasus, and LTX research teams	U.S. Spherical Tokamak Program Initiatives for the Next Decade
T. Munsat (U. Colorado), N.C. Luhmann, Jr. (UC Davis), B. Tobias (PPPL)	Center for Imaging and Visualization in Tokamak Plasmas
R. R. Parker, G-S. Baek, P. T. Bonoli, B. LaBombard, Y. Lin, M. Porkolab, S. Shiraiwa, G. M. Wallace, S. J. Wukitch, D. Whyte, MIT PSFC	RF Actuators for Steady-State Tokamak Development
C. K. Phillips PPPL and P. T. Bonoli MIT, L. A. Berry, XCEL, N. Bertelli, PPPL, D. D'Ippolito, Lodestar, D. L. Green, ORNL, R.W. Harvey, CompX, E. F. Jaeger, XCEL, J. Myra, Lodestar, Y. Petrov, CompX, M. Porkolab, S. Shiraiwa, MIT, D.N. Smithe, TechX, E. J. Valeo, PPPL, and J. C. Wright, MIT	International Collaborative Initiative for RF Simulation Models in support of ITER and the ITER Integrated Modeling Program: Status and Priorities
C. K. Phillips PPPL and P. T. Bonoli MIT, L. A. Berry, XCEL, N. Bertelli, PPPL, D. D'Ippolito, Lodestar, D. L. Green, ORNL, R.W. Harvey, CompX, E. F. Jaeger, XCEL, J. Myra, Lodestar, Y. Petrov, CompX, M. Porkolab, S. Shiraiwa, MIT, D.N. Smithe, TechX, E. J. Valeo, PPPL, and J. C. Wright, MIT	International Collaborative Initiative for RF Simulation Models in support of ITER and the ITER Integrated Modeling Program: Proposed Initiative
Leanne Pitchford, LAPLACE, CNRS and University of Toulouse III, France	The Plasma Data Exchange Project and the LXCat Platform
Leanne Pitchford, LAPLACE, CNRS and University of Toulouse, France	Resource request for the Plasma Data Exchange Project and the LXCat platform
M. Podesta, D. Darrow, E. Fredrickson, G.-Y. Fu1, N. Gorelenkov, J. Menard, and R. White, PPPL, J. K. Anderson, UWisc, W. Boeglin, FIU, B. Breizman, UTexas, D. Brennan, Princeton U., A. Fasoli, CRPP/EPFL, Z. Lin, UCLA Irvine, S. D. Pinches and J. Snipes, ITER, S. Tripathi, UCLA LA, M. Van Zeeland, GA	Development of tools for understanding, predicting and controlling fast ion driven instabilities in fusion plasmas
S. Prager, Princeton Plasma Physics Laboratory	The PPPL Perspective on Ten Year Planning in Magnetic Fusion
R. Prater, R.I. Pinsker, V. Chan, A. Garofalo, C. Petty, M. Wade, GA	Optimize Current Drive Techniques Enabling Steady-State Operation of Burning Plasma Tokamaks
R. Raman, UWash, T.R. Jarboe, UWash, J.E. Menard, S.P. Gerhardt and M. Ono, PPPL	Development of a Fast Time Response Electromagnetic Disruption Mitigation System
R. Raman, UWash, T.R. Jarboe, and B.A. Nelson,	Simplifying the ST and AT Concepts

UWash, T. Brown, J.E. Menard, D. Mueller, and M. Ono, PPPL	
J. Rapp, D.L. Hillis, J.P. Allain, J.N. Brooks, H.Y. Guo, A. Hassanein, D. Hill, R. Maingi, D. Ruzic, O Schmitz, E. Scime, G. Tynan	Material Facilities Initiative: MPEX and FMITS
S.A. Sabbagh and J.M. Hanson, Columbia U., N. Commaux, ORNL, N. Eidietis, R. La Haye, and M. Walker, GAVE, S.P. Gerhardt, E. Kolemen. J.E. Menard, PPPL, B. Granetz, MIT, V. Izzo, UCSD, R. Raman, U. WASHINGTON, S. Woodruff, Woodruff Scientific	Critical Need for Disruption Prediction, Avoidance, and Mitigation in Tokamaks
Alla Safronova, Physics Department, University of Nevada	Significance of Atomic Physics for Magnetically Confined Fusion and High-Energy-Density Laboratory Plasmas, Status, priorities, and initiatives white paper
J.S. Sarff, A.F. Almagri, J.K. Anderson, D.L. Brower, B.E. Chapman, D. Craig, D.R. Demers, D.J. Den Hartog, W. Ding, C.B. Forest, J.A. Goetz, K.J. McCollam, M.D. Nornberg, C.R. Sovinec, P.W. Terry, and Collaborators	Opportunities and Context for Reversed Field Pinch Research
Ann Satsangi, OFES DOE	Discovery Plasma Science: A question on Facilities
T. Schenkel, P. Seidl, W. Waldron, A. Persaud, LBNL, John Barnard and Alex Friedman, LLNL, E. Gilson, I. Kaganovich, and R. Davidson, PPPL, A. Minor and P. Hosemann, University of California, Berkeley	Discovery Science with Intense, Pulsed Ion Beams
Peter Seidl, Thomas Schenkel, Arun Persaud, and W.L. Waldron, LBNL, John Barnard and Alex Friedman, LLNL, Erik Gilson, Igor Kaganovich, and Ronald Davidson, PPPL	Heavy-Ion-Driven Inertial Fusion Energy
David R. Smith, UWISC	Data science and data accessibility at national fusion facilities
E.J. Strait, GA	Establishing the Basis for Sustained Tokamak Fusion through Stability Control and Disruption Avoidance: (I) Present Status
E.J. Strait, GA	Establishing the Basis for Sustained Tokamak Fusion through Stability Control and Disruption Avoidance: (II) Proposed Research
William Tang, PPPL	Validated Integrated Fusion Simulations Enabled by Extreme Scale Computing
P.W. Terry UWISC, Peter Catto MIT, Nikolai Gorelenkov PPPL, Jim Myra LODESTAR, Dmitri Ryutov LLNL, Phil Snyder GA, and F.	Role of Analytic Theory in the US Magnetic Fusion Program

Waelbroeck UTEXAS	
The University Fusion Association	The Role of Universities in Discovery Science
Mickey R. Wade, GA, for the DIII-D Team	Developing the Scientific Basis for the Burning Plasma Era and Fusion Energy Development, (A 10-Year Vision for DIII-D)
Anne White, Paul Bonoli, Bob Granetz, Martin Greenwald, Zach Hartwig, Jerry Hughes, Jim Irby, Brian LaBombard, Earl Marmar, Miklos Porkolab, Syun'ichi Shiraiwa, Rui Vieira, Greg Wallace, and Graham Wright, MIT, David Brower, Neal Crocker, and Terry Rhodes, UCLA, Walter Guttenfelder, PPPL, Chris Holland, UCSD, Nathan Howard, ORISE, George McKee, UWISC	A new research initiative for "Validation Teams"
G. Wurden, S. Hsu, T. Intrator, C. Grabowski, J. Degnan, M. Domonkos, P. Turchi, M. Herrmann, D. Sinars, M. Campbell , R. Betti , D. Ryutov, B. Bauer, I. Lindemuth, R. Siemon, R. Miller, M. Laberge, M. Delage	Magneto - Inertial Fusion
D. Whyte, MIT Plasma Science and Fusion Center	Exploiting high magnetic fields from new superconductors will provide a faster and more attractive fusion development path
X. Q. Xu, LLNL	International collaboration on theory, validation, and integrated simulation
J. Freidberg, E. Marmar, MIT, H. Neilson , M. Zarnstorff, PPPL	The Case for QUASAR (NCSX)
Thomas Klinger, Hans-Stephan Bosch, Per Helander, Thomas Sunn Pedersen, Robert Wolf Max-Planck Institute for Plasma Physics	A Perspective on QUASAR
Thomas Klinger, Hans-Stephan Bosch, Per Helander, Thomas Sunn Pedersen, Robert Wolf Max-Planck Institute For Plasma Physics	Status And Prospects Of The U.S. Collaboration With The Max-Planck Institute For Plasma Physics On Stellarator Research On The Wendelstein 7-X Device
H. Neilson, D. Gates, M. Zarnstorff, S. Prager, PPPL	Management Strategy for QUASAR
Members of the National Stellarator Coordinating Committee	Control of High-Performance Steady-State Plasmas: Status of Gaps and Stellarator Solutions
Members of the National Stellarator Coordinating Committee	Solutions for Steady-State High Performance MFE: A U.S. Stellarator Program for the Next Ten Years
Oliver Schmitz, UWISC, on behalf of U.S. stellarator collaborators	Development of 3-D divertor solutions for stellarators through coordinated domestic and

	international research
Matt Landreman, University of Maryland, on behalf of the US Stellarator Coordinating Committee	3D theory and computation: A cost-effective means to address "long-pulse" and "control" gaps

Appendix F: Community Workshops and Presentations

Week 8 (2-6 June): 1st Panel Meeting – Mon 1830 to Friday 1300 with 3-days of talks
Week 13 (7-11 July): 2nd Panel Meeting – Mon 1830 to Friday 1300 with 3-days of talks

3-5 June, Gaithersburg Marriott Washingtonian Center, 301-590-0044
9751 Washingtonian Boulevard, Gaithersburg, MD. 20878

"*Heat Fluxes, Neutron Fluences, Long Pulse Length*" [i.e., *Burning Plasma: Long Pulse*]
Tues (12 talks):

0830 **Fonck**, *Perspectives on 10-Year Planning for the Fusion Energy Sciences Program*
0900 **Kessel**, *Critical Fusion Nuclear Material Science Activities Required Over the Next Decade to Establish the Scientific Basis for a Fusion Nuclear Science Facility*
0930 **Abdou**, *Scientific Framework for Advancing Blanket/FW/Tritium Fuel Cycle Systems towards FNSF & DEMO Readiness*
1000 **Wirth** *An Integrated, Component-level Approach to Fusion Materials Development*
1030 Break
1045 **Hill**, *Develop the Basis for PMI Solutions for FNSF*
1115 **Callis**, *Applied Scientific Research for Blanket and Nuclear Components to Enable Design of the Next-Step BP Device*
1145 Lunch
1345 **Zarnstorff,** *U.S. strategies for an innovative stellarator-based FNSF*
1415 **Buttery**, *Establishing the Physics Basis for Sustaining a High* β *BP in Steady-State*
1445 **Prater**, *Optimize Current Drive Techniques Enabling S-S Operation of BP Tokamaks*
1515 Break
1535 **Garofalo**, *Leveraging International Collaborations to Accelerate FNSF Development*
1605 **Harris**, *Alternatives and prospects for development of the U.S. stellarator program*
1635 **Landreman**, *3D theory & computation as a major driver for advances in stellarators*

"*Astrophysical Phenomena, Plasma Control Important for Industrial Applications*"
[i.e., *Discovery Science*]
Wednesday (12 talks):

0840 **Glenzer**, *High-Energy Density science at 4th generation Light Sources*
0910 **Seidl**, *Heavy-Ion-Driven Inertial Fusion Energy*
0940 **Schenkel**, *Discovery Science with Intense, Pulsed Ion Beams*
1010 Break
1030 **Jarboe**, *A pre-Proof-of-Principle experiment of a spheromak formed and sustained by Imposed Dynamo Current-Drive (IDCD)*
1100 **Ji**, *Major Opportunities in Plasma Astrophysics*
1130 Lunch
1315 **Petrasso**, *Oppositely directed laser beams at OMEGA-EP for advancing HED Physics: A Finding & Recommendation of the Omega Laser Users Group*

1345 **Fox**, *Lab astrophysics & basic plasma physics with HED, laser-produced plasmas*
1415 **Drake**, R. P, *Challenges and Opportunities in High-Energy-Density Lab Plasmas*
1445 Break
1505 **Kushner**, *Science Issues in Low Temperature Plasmas: Overview, Progress, Needs*
1535 **Raitses**, *Plasma Science Associated with Modern Nanotechnology*
1605 **Donnelly**, *Ignition Delays in Pulsed Tandem Inductively Coupled Plasmas System*
1635 **Kaganovich**, *DoD's Multi-Institution Collaborations for Discovery Science*

"*Discovery Science, Advanced Measurement for Validation,*" [i.e., *Discovery Science*]
Thursday (12 talks):

0840 **Wurden**, *Long-pulse physics via international stellarator collaboration*
0910 **Schmitz**, *Development of 3-D divertor solutions for stellarators through coordinated domestic and international research*
0940 **Krstic**, *Multiscale, integrated divertor plasma-material simulation*
1010 Break
1030 **Sarff**, *Opportunities and Context for Reversed Field Pinch Research*
1100 **Mauel**, *Multi-University Research to Advance Discovery Fusion Energy Science using a Superconducting Laboratory Magnetosphere*
1130 Lunch
1315 **Ji**, *Importance of Intermediate-scale Experiments in Discovery Plasma Science*
1345 **Efthimion**, *Office of Science Partnerships and Leveraging of Discovery Science*
1415 **Brennan**, *The Role of Universities in Discovery Science in the FES Program*
1445 Break
1505 **Whyte**, *Exploiting high magnetic fields from new superconductors will provide a faster and more attractive fusion development path*
1535 **Minervini**, *Superconducting Magnets Research for a Viable U.S. Fusion Program*
1605 **Parker**, *RF Actuators for Steady-State Tokamak Development*
1635 **LaBombard**, *A nationally organized, advanced divertor tokamak test facility is needed to demonstrate plasma exhaust and PMI solutions for FNSF/DEMO*

8-10 July, Gaithersburg Marriott Washingtonian Center, 301-590-0044
9751 Washingtonian Boulevard, Gaithersburg, MD. 20878

Tuesday July 8 Meeting (16 talks)
0830 **Zohm**, *ASDEX-Upgrade*
0905 **Horton**, *JET*
0940 **Guo**, *EAST*
1015 Break
1045 **Kwak**, *KSTAR*
1120 **Kamada**, The *JT-60SA research regimes for ITER and DEMO*
1155 **Litaudon**, *EUROfusion Roadmap*
1225 **Litaudon**, *WEST facility*
1300 Lunch
1415 **Menard**, *NSTX-U: ST research to accelerate fusion development*
1445 **Majeski**, *LTX: Exploring the advantages of liquid lithium walls*
1515 **Fonck**, *Initiatives in non-solenoidal startup and edge stability dynamics at near-unity aspect ratio in the PEGASUS experiment*
1545 Break

1600 **Marmar,** *Successful completion of Alcator C-Mod, and transition to a new, advanced divertor facility (ADX) to solve key challenges in PMI and development of the steady-state tokamak: Maintaining world-leadership on the high magnetic field path to fusion*
1630 **Wade**, *DIII-D 10-year vision: Develop the scientific basis for burning plasma experiments and fusion energy development*
1700 **Raman**, *Simplifying the ST and AT concepts*
1730 **Guo**, *Developing plasma-based divertor solutions for next step devices*
1800 **Coppi**, *The high-field compact line of experiments: From Alcator to Ignitor & beyond*
1830 **Freidberg,** *MIT-PSFC makes the case for QUASAR*
1900 Public Meeting Adjourns for the day

Wednesday July 9 Meeting (15 talks)
0830 **Greenwald**, *Implications and lessons from 2007 strategic planning activity and subsequent events: A personal view*
0900 **Meade**, *U.S. road map activity*
0930 **Taylor**, *A U.S. domestic program in the ITER era*
1000 **Greenfield**, *USBPO high priority research in support of ITER*
1030 Break
1100 **Boivin**, *Enhanced Validation of Performance-Defining Physics through Measurement Innovation*
1130 **White**, *Advanced diagnostics for validation in high-performance toroidal confinement experiments*
1200 **Crocker**, *Validating electromagnetic turbulence and transport effects for burning plasmas*
1230 **Brower**, *A burning plasma diagnostic technology initiative for the U.S. magnetic fusion energy science program*
1300 Lunch
1445 **Petty**, *Preparing for burning plasma operation and exploitation in ITER*
1515 **Sabbag**h, *Critical need for disruption prediction, avoidance, and mitigation in tokamaks*
1545 **Strait**, *Stability control, disruption avoidance, and mitigation*
1615 **Jardin**, *Increased understanding and predictive modeling of tokamak disrupttions*
1645 Break
1700 **Podesta**, *Development of tools for understanding, predicting and controlling fast-ion-driven instabilities in burning plasmas*
1730 **Fu**, *Integrated simulation of performance-limiting MHD and energetic particle instabilities with micro-turbulence*
1800 **Goldston**, *A strategy for resolving problems of plasma-material interaction for FNSF*
1830 Public Meeting Adjourns for the day

Thursday July 10 Meeting (16 talks)
0830 **Tang**, *Validated integrated fusion simulations enabled by extreme scale computing*
0900 **Snyder**, *Crossing the threshold to prediction-driven research and device design*
0930 **Hammett**, *Integrated computing initiative to predict fusion device performance and study possible improvements*
1000 **Chang**, *First-principles simulation of whole fusion device on leadership class high-performance computers in collaboration with ASCR scientists*
1030 Break
1100 **Xu**, *International collaboration on theory, validation, and integrated simulation*
1130 **Phillips**, *International collaborative initiative for RF simulation models in support of ITER and the ITER integrated modeling program*

1200 **Catto**, *Unique opportunities to advance theory and simulations of RF heating & current drive and core & pedestal physics at reactor relevant regimes in the Advanced Divertor Experiment*
1230 **Terry**, *Role of analytic theory in the U.S. magnetic fusion program*
1300 Lunch
1415 **Hillis**, *Materials facilities initiative*
1445 **Unterberg**, *Advanced Materials Validation in Toroidal Systems for Next-Step Devices*
1515 **Maingi**, *A liquid-metal plasma-facing-component initiative*
1545 **Jaworski**, *Liquid metal plasma-material interaction science and component development toward integrated demonstration*
1615 **Allain**, *Establishing the surface science and engineering of liquid-metal plasma-facing components*
1645 Break
1700 **Baylor**, *Plasma controlling and sustainment technologies that enable long-pulse burning plasma science*
1730 **Gekelman**, *The Basic Plasma Science Facility – Upgrade for the next decade & beyond*
1800 **Prager**, *The PPPL perspective on the charge to the FESAC strategic planning panel*
1830 Public Meeting Adjourns for the day

Appendix G: Leveraging and Partnership Opportunities with DOE, other Federal and International Partners

Narratives

Chapter 5, concerning leveraging and partnership opportunities, summarized opportunities for the U.S. fusion energy program by means of two tables, relegating more detailed discussion to this appendix. Below are descriptions of each of these opportunities, organized by the Office within DOE Science (ASCR, HEP, NP, BES), Other DOE programs (FE, EERE, NE, NNSA), Other non-DOE federal programs (NSF, NIST, DOD, NASA), and international partnerships.

DOE Office of Science Programs

ADVANCED SCIENTIFIC COMPUTING RESEARCH (ASCR)

The U.S. is recognized as the world leader in magnetic fusion theory, simulation, and computation. This capability would not be as strong without the FES-ASCR partnership, which is exemplary within the Office of Science. The partnership of vibrant collaborations is enabled by the jointly-sponsored Scientific Discovery through Advance Computing (SciDAC) Program and the use of ASCR leadership class high-performance computer facilities at Oak Ridge, Argonne, and Berkeley. SciDAC contributes to the FES goal of developing the predictive capability needed for a sustainable fusion energy source by exploiting the emerging capabilities of petascale computing and associated progress in software and algorithm development. This has resulted in projects that develop applications of high physics fidelity simulation codes to advance the fundamental science of magnetically confined plasmas. Potentially new partnerships include the ASCR Applied Mathematics, Computer Science, and

Uncertainty and Quantification (UQ) Programs, and their Exascale Co-Design Centers (e.g., the Center for Exascale Simulation of Advanced Reactors led by Argonne National Laboratory).

BASIC ENERGY SCIENCES (BES)

FES and BES have established a successful partnership with the construction and operation of the Materials in Extreme Conditions (MEC) end station at the Linac Coherent Light Source, a BES National User Facility at SLAC. Despite HEDLP program reductions within Discovery Plasmas Science, FES has maintained this partnership.

In addition, there has been a 30-year fusion materials irradiation program, in collaboration with Japan, which uses the HFIR Reactor, a BES National User Facility. Accomplishments included studies of low activation ferritic steels irradiated up 120 displacements per atom, and advanced radiation resistant Silicon Carbide composites and ODS steels that have high resistance to high temperature creep. The silicon carbide and ODS steels also benefit advanced fission reactors.

Important new opportunities include high fidelity characterization of irradiated materials and in-situ corrosion mechanisms using BES materials characterization user facilities. There are potentially important synergies between fusion materials research and fundamental BES research programs on defects in materials and mechanical properties. Fusion-specific conditions (relevant He/dpa irradiations, etc.) will generally only be supported by FES, but important fundamental radiation effects information may be gleaned from some BES projects. Other opportunities include access to characterize irradiated materials at synchrotron beam lines (including neutron irradiated and possible in situ ion irradiation), and world class electron microscopy characterization facilities have also been heavily utilized by fusion materials researchers over the years.

The most cost-effective approach to develop a fusion materials irradiation facility is to use one of the existing MW-level spallation sources. FES has supported an engineering design study for a Fusion Materials Irradiation Test Stand (FMITS) at the Spallation Neutron Source at Oak Ridge that is operated by BES. The benefits to FES are substantial, while the benefits to BES are not apparent. Acceptable risk levels for SNS operations must be achieved.

HIGH ENERGY PHYSICS (HEP)

Superconducting magnets is a critical technology for long-pulse experiments and will determine the freedom in design parameters, manufacturability, and cost of an actual fusion plant. Currently the magnet program within the Office of Fusion Energy Sciences (FES) is modest but has benefited from a collaborative relationship with the Office of High Energy Physics (HEP) for many years, which has a deeper and better funded magnet effort as part of its General Accelerator R&D program. . Historically, the coordination on Nb3Sn-based magnets has been strong, where FES and HEP have exchanged expertise in reviews, and jointly funded Small Business Innovative Research solicitations. One driver for HEP's magnet development in recent years has been the Muon Ionization Cooling Experiment (MICE), which the recent P5 report has recommended for early termination. Nevertheless, the US LHC Accelerator Research

Program (US LARP) continues to support magnet development at BNL, FNAL and LBNL.

In regard to High Temperature Superconductor (HTS) research, FES and HEP have collaborated fruitfully in the past, but their fundamental interests in HTS are diverging (higher field ring magnets for HEP, lower cryopower requirements for FES) and consequently so are their specific pursuits in conductors. Nevertheless, there is interest in sharing of conductor testing and testing facilities. In light of the LHC upgrade, CERN represents a potentially interesting partner for FES. The National High Magnetic Field Laboratory (NHMFL), supported by the NSF, performs research on very high field HTS magnets and some of that work is strongly congruent with the interests of FES. In fact, the Magnet Lab has adopted the cable-in-conduit conductor (CICC) for the design of all their large bore high field magnets.

NUCLEAR PHYSICS (NP)

Improved fast-neutron cross sections are a pressing need for fusion reactor materials. As an example, it is important to reduce the error bars in the fast neutron cross sections for tungsten, the material chosen for the ITER diverter. Recently the DOE Office of Nuclear Physics Nuclear Data Program undertook a program-wide review and a radical updating of their mission and modus operandi, the end of which represents a significant opportunity for the Fusion Energy Program going forward. In contrast to how that program operated in the past (curation and archiving of published data largely by A-chain [mass number]), the new program identifies Nuclear Engineering and Applications as a primary client for nuclear data, prioritizes the evaluation of nuclear data according to community needs, and supports experimentation to fill in critical missing data. The new mission includes the support of education and training of students and will ensure the continuity of nuclear data expertise for coming generations. This is a welcome development and the fusion community should take advantage of the opportunity by doing an internal prioritization of their nuclear data needs and communicate with the Nuclear Data Office.

Other DOE Programs

FOSSIL ENERGY (FE)

Fusion materials systems based on advanced ferritic/martensitic steels share several of the high performance structural materials issues encountered in recent supercritical Rankine cycle and proposed ultra-supercritical Rankine cycle fossil energy plants. These issues include development of new steels that are resistant to aging and thermal creep degradation at high temperatures, as well as some aspects of thermal creep-fatigue structural design criteria. Indeed, the current leading approach for developing new high performance steels in both fossil and fusion energy systems is based on computational thermodynamics to identify promising new compositions and thermomechanical treatments that will produce ultra-fine scale, highly stable precipitates. Much of the steel production, joining, and mechanical testing infrastructure, as well as some of the corrosion test equipment, are directly relevant for fusion. The FE Carbon Capture Simulation Initiative at NETL is a hub-like entity that should have some synergies with FES, such as the linear and nonlinear partial differential equation solvers, parallel communication constructs and libraries, verification and validation and uncertainty quantification tools and methodologies, build and testing tools, and data analytics.

ENERGY EFFICIENCY & RENEWABLE ENERGY (EERE)

Advanced materials processing studies performed for EERE programs are directly relevant to fusion structural materials applications, including fundamental investigations on the utility of additive manufacturing for producing high-performance components that would be difficult or impossible to fabricate using conventional means, as well as studies exploring the possibility of incorporating embedded sensors and other "smart material" systems. The EERE studies are complementary to BES materials research in that they typically focus on industrial-scale practical issues, similar to the case for FE programs.

The EERE Critical Materials Institute (CMI) Hub, led by the Ames Laboratory, is focused on searching for replacement materials for rare earth magnets that are less relevant to fusion. However, the Hub construct could offer a better way to manage future FES large and complex programs. The CMI brings together scientists and engineers from diverse disciplines to address challenges in critical materials, including mineral processing, manufacture, substitution, efficient use, and end-of-life recycling. The institute also integrates scientific research, engineering innovation, manufacturing and process improvements in order to find a holistic solution to the materials challenges facing the nation.

NUCLEAR ENERGY (NE)

NE investments in the past several decades in infrastructure and materials research will be of significant value to FES as it moves toward a Fusion Nuclear Science (FNS) Program. These investments include hot cell facilities across the DOE complex, modeling and simulation, fast reactor materials development, and waste management.

Several leveraging opportunities exist between fusion and fission technologies. In particular, many of the structural materials and coolant systems for fusion and Generation IV fission reactor concepts are common to both (e.g., ferritic/martensitic steels, oxide dispersion strengthened steels, ceramic matrix composites, liquid lead alloy and alkali metal coolants, and helium-cooled systems). The structural materials for fusion and Generation IV fission concepts share qualitatively similar requirements to withstand high displacement damage and high operating temperature environments and require comparably high performance specifications. Valuable information on operating large nuclear reactors is also of practical importance for fusion designs.

Additional opportunities exist with NE development and application of advanced modeling and simulation tools for nuclear fuel, nuclear reactors, fuel cycle, etc. The most prominent are the Consortium for Advanced Simulation of Light Water Reactors (CASL) Hub, led by Oak Ridge National Laboratory, and the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program led by Argonne National Laboratory. Additionally, there are the Light Water Reactor Sustainability and Fuel Cycle R&D

Programs. FES connections would include infrastructure, multi-physics coupling, V&V/UQ, material science, and radiation transport.

Finally, NE could be a useful interface with the NRC in managing fusion nuclear safety and regulatory requirements. Future fusion power plants will offer a fundamentally different safety paradigm compared with fission reactors and should follow a tailored licensing approach very different from fission; otherwise this could be a barrier to fusion energy development. At present, no country has fusion-specific regulatory framework for power plant construction and operation, although DOE has safety guidelines for U.S. experimental fusion facilities, as does France for the ITER facility. Consultation with regulatory experts (NRC, DOE, utilities, foreign regulatory bodies) is needed to understand options for a U.S. fusion regulatory approach.

NATIONAL NUCLEAR SECURITY ADMINISTRATION (NNSA)

NNSA has two significant partnerships with the Office of Science relevant to FES mission: Advanced Scientific Computing (ASC) and High Energy Density Laboratory Plasmas (HEDLP). High performance computer (HPC) platforms have been developed for visualization and data analytics, multi-physics coupling, MHD, plasma physics, turbulence, charged particle transport, and radiation transport. The NNSA-ASCR partnership to develop the next generation HPC (TRINITY – NERSC-8) will enable fusion scientists to maintain world-leading performance. There is also the NNSA Predictive Science Academic Alliance Program created to establish validated, large-scale, multidisciplinary, simulation-based “Predictive Science” as major academic and applied research programs.

An important element of the FES HEDLP program is the Joint NNSA-SC program that supports discovery plasma science research addressing critical issues in inertial fusion energy sciences and non-mission-driven high energy density plasmas. The program also explores ways to create, probe, and control new states of matter at very high energy densities. However, this partnership has suffered in recent years from reduced FES support. Remaining FES program resources are focused on their LCLS MEC Station. Significant HEDLP discovery science opportunities exist on several world leading NNSA-operated laser and pulsed-power facilities. FES support of academic research teams to use NNSA-supported facilities represents a cost-effective option for FES discovery science. FES potential funding of the users of these facilities would go a long way toward building FES’s reputation and engaging NNSA in HEDLP science workforce development.

Non-DOE Federal Programs

NATIONAL SCIENCE FOUNDATION (NSF)

The NSF/DOE Partnership in Basic Plasma Science and Engineering was developed in part in response to the 1995 National Research Council report, Plasma Science, that reaffirmed plasma science as a fundamental discipline covering broad set of scientific and technological areas. The purpose of the partnership is to: encourage synergy and complementarity between the research programs supported by the two agencies; provide enhanced opportunities for university-based research in fundamental processes in plasma science and engineering; stimulate plasma science and engineering education in U.S. universities, and; avoid duplication of effort. Research activities directly related to fusion energy are excluded.

Support by both agencies is excellent as evidenced by joint program announcements, and reviews of proposals and project performances. The agencies also share oversight and support for the operation of the world's only basic plasma physics user facility, the Large Area Plasma Device at UCLA. This facility enables a broad group of plasma researchers to carry out experiments that would not be possible on smaller facilities at their respective institutions. Mutual benefits include credibility in basic plasma science pursuits and stewardship, synergistic budget elasticity, and the ability to conduct joint General Plasma Science programs between DOE Laboratories and university Plasma Science Centers.

NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY (NIST)

In general, NIST offers the potential for complementary materials R&D that spans everything from nanoscience to advanced manufacturing. Currently there efforts being made to establish a strong collaboration with NIST, but the opportunity should be pursued.

Since the early 1960s, NIST has been a leading center in plasma spectroscopy. Critical compilations of energy levels, wavelengths, and atomic transition probabilities, as well as benchmark experimental measurements of atomic data, have set a standard that is now embodied in the online Atomic Spectra Database and associated bibliographic databases. This resource serves in excess of 70,000 separate requests for data every month. Many of the requests come from researchers who use the data for fusion plasma diagnostics or simulations related to fusion energy. The database has been supported by NIST and DOE since 1975.

NIST plasma-relevant programs are miniscule compared to FES, so NIST could significantly increase its efforts on plasma-related atomic spectroscopy with a small DOE-FES investment (less than $1M/year). This investment could have high impact on specific research problems for discovery plasma science, specifically low-temperature plasmas.

DEPARTMENT OF DEFENSE (DOD)

FES-DOD partnerships have been challenging because of their mission approach to funding research. Several DOD branches have capabilities and infrastructure complementary to those from FES. For example, the Computational Research and Engineering Acquisition Tools and Environments (CREATE) program, started by a former FES principal investigator, is designed to improve DOD acquisition with advanced computational engineering design tools. Synergy with FES includes infrastructure, multi-physics, and V&V/UQ.

The Air Force Office of Scientific Research has been a strong supporter of applied plasma science for their DOD mission, most notably high-power microwaves, novel acceleration mechanisms, and electrodynamics through their Plasma and Electro-Energetic Physics Program. Infrastructure at the Air Force Research Laboratory (AFRL) has been used by the FES HEDLP program.

The Naval Research Laboratory (NRL) is involved in activities related to the understanding of HEDLP produced by pulsed power generators or high intensity, short pulse lasers. It has made significant contributions to the design, development, prediction, and analysis of intense plasma radiation sources by employing state-of-the-art atomic physics, radiation physics and magneto-hydrodynamics modeling. It is also working on interactions of an ultra-intense short pulse laser with a thin planar target. NRL also has research efforts in the science and technologies of inertial confinement fusion (supported by NNSA), the development and applications of high-power pulsed electron beams.

The Defense Threat Reduction Agency (DTRA) also supports individual grants to FES PIs in HED Physics.

NATIONAL AERONAUTICS & SPACE ADMINISTRATION (NASA)

FES and NASA share an interest in high-heat flux technologies and high-temperature structural materials. Currently there are no active FES-NASA collaborations, but there has been some limited mutually beneficial research on development of ceramic matrix composites such as SiC/SiC.

NASA also represents an opportunity for advancing discovery in plasma science. Taking advantage of this opportunity does not require a partnership because NASA issues funding opportunity announcements of its own. While the plasma-relevant programs of NASA outweigh DOE-FES in terms of strength, the Panel was informed that FES outreach to NASA has not been successful, possibly because of different missions, cultures, and the lack of mutual benefit.

International Partnership Opportunities

Two thorough assessments of international collaboration opportunities were performed by a community task force commissioned by the U.S. Burning Plasma Organization in 2011 and by FESAC in 2012 [Appendix H]. Although these studies did not consider trade-offs between domestic and international programs in the context of constrained FES budgets, their evaluation criteria, recommended modes of collaboration and research priorities (extending high-performance regimes to long pulse, development and integration of plasma wall solutions for fusion, and burning plasma research in advance of ITER) remain valid..

Building on the 2012 FESAC report, the Panel also spent considerable time comparing FES international collaborations with those supported by the DOE High Energy Physics (HEP) Program. One might be able to draw analogies between large FES and HEP facilities, e.g., a particle physics detector and a fusion diagnostic, and particle physics accelerator systems (e.g., vacuum, cavities, magnets, RF, instrumentation and controls, targets and beam stops, modeling and simulation) and tokamak systems (e.g., vacuum, neutral beam injectors, fueling, magnets, RF, instrumentation and controls, first walls and divertors, modeling and simulation). While mutually beneficial international opportunities to produce fusion science on leading edge fusion facilities were apparent, the Panel noted some reluctance from the fusion community to seize those opportunities. A similar reaction occurred with the HEP community physics several years ago, but those international collaborations are now welcomed, with a significant fraction of personnel time and effort occurring at home institutions designing, building, testing, and calibrating detector and accelerator systems and sub-systems, and performing remote shifts, modeling, and analysis of international facility data.

While a majority of high energy physicists in the U.S. perform research at various global facilities, FES participation in international experiments is an order of magnitude lower. Moreover, non-ITER international partnership trends over the past several years reveal a reduction in FES support at a time when there have been no new MFE U.S. facilities and only one major upgrade in the last 15 years. At the same time, several new and upgraded fusion facilities have, or will, become available in Asia and Europe (Table II). Lessons and practices reported in the 2012 International Collaborations FESAC Report provide a good starting point. The Panel insists, however that a good strategic plan should not stipulate "our" machine or "their" machine, but the "right" machine – the U.S. should engage in international experiments where there is a clear and compelling need for specific data.

In addition to the large fusion plasma experimental facilities, there have been numerous long-standing effective international collaborations, ranging from information sharing via IEA working groups that has accelerated the development of several high performance fusion materials, to funds-in formal bilateral collaborations with JAEA and MEXT researchers that utilize unique U.S. facilities such as the RTNS-II D-T fusion neutron facility, the Tritium Science Test Assembly, and high flux fission reactors and advanced hot cell facilities.

Similar international collaborations have been useful for the design of fusion neutron sources such as the proposed International Fusion Materials Irradiation Facility (IFMIF), based on an earlier U.S. design. There are potential opportunities for U.S. fusion researchers to gain access to unique foreign facilities such as large scale corrosion and thermomechanical test loop facilities, high heat flux and plasma material interaction facilities, tokamak diverter exposure facilities (WEST, EAST, ASDEX, etc.), in tritium facilities, and with operational, safety and regulatory experts on how to best develop a performance-based regulatory basis for fusion power (Canada, IAEA, JET, ITER).

Finally, the Panel recognizes FES partnerships enabled by the International Atomic Energy Agency (IAEA) and the International Energy Agency (IEA). As a member of the IAEA, the U.S. benefits from information collected and shared at the IAEA fusion biannual Nuclear Fusion Conference and Journal, workshops, committees, and coordinated research projects (CRPs). Leveraging this type of international coordinated research with domestic programs would enable greater impact for FES investments. Some fusion science CRPs have been performed on several topics relevant to next-step fusion devices, ODS steels and irradiation facilities. Of course, IAEA also facilitates international communication via the biannual Nuclear Fusion conference, its journal, and other relevant activities. In addition to the materials working group, the IEA has a large number of working groups in nearly all areas t of fusion science, including he fusion technology and environment, safety and economics. The working groups typically meet at least annually.

Appendix H: References

In Chapter 4: Discovery Plasma Science, 20 citations to prior reports, prior studies, and various websites are made, which are listed here.

1. NRC Plasma 2010 Plasma Science Committee report [National Research Council. *Plasma Science: Advancing Knowledge in the National Interest*. Washington, DC: The National Academies Press, 2007, Copyright © National Academy of Sciences]

2. For a description of NSF/DOE Partnership in Basic Plasma Science and Engineering, see http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5602

3. Low Temperature Plasma Science Workshop report (2007) details available at http://science.energy.gov/fes/news-and-resources/workshop-reports/

4. Research Opportunities in Plasma Astrophysics report (2011) details available at http://w3.pppl.gov/conferences/2010/WOPA/index.html

5. See BaPSF publication list at http://plasma.physics.ucla.edu/page/publications.html

6. See Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems at the University of Michigan Research Highlights at http://doeplasma.eecs.umich.edu/research

7. For more information about the LCLS MEC, see https://portal.slac.stanford.edu/sites/lcls_public/Instruments/mec/Pages/default.aspx

6. See the LCLS MEC publication list at https://portal.slac.stanford.edu/sites/lcls_public/Pages/Publications_MEC.aspx

7. FESAC Toroidal Alternates Panel report (2008) details available at http://science.energy.gov/fes/fesac/reports/ and at https://fusion.gat.com/tap/

8. For background information about MST, see http://plasma.physics.wisc.edu/viewpage.php?id=mst

9. See MST publication list at http://plasma.physics.wisc.edu/publications/publications-for-experiment.php?experiment=MST

10. The most recent HTPD conference website with links to papers presented can be viewed at http://web.ornl.gov/sci/fed/HTPD2014/

11. Details about the NSF's Major Research Instrumentation Program can be found at http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5260.

12. For background information on BAPSF, see http://plasma.physics.ucla.edu/index.html

15. For background information on FLARE, see http://mrx.pppl.gov

16. For background information on MPDX, see http://plasma.physics.wisc.edu/mpdx

17. For background information on MDPX, see http://psl.physics.auburn.edu/research/magnetized-dusty-plasmas.html

16. The HEDLP Basic Research ReNeW report can be found at http://science.energy.gov/fes/news-and-resources/workshop-reports/

19. FESAC Panel on HEDLP Report (January 2009) details available at http://science.energy.gov/fes/fesac/reports/

20. For details about the "Committee of Visitors" see http://science.energy.gov/sc-2/committees-of-visitors/

21. For the SC description of User Facilities and User Programs see http://science.energy.gov/user-facilities/

A major reference for the Panel is the 2009 Report of the Research Needs Workshop (ReNeW) for Magnetic Fusion Energy Sciences, which identified the research frontiers of the fusion program and outlined eighteen Thrust activities that will most effectively advance those frontiers.

References used are listed here, with website links available on the FESAC Strategic Planning Panel website and elsewhere: https://www.burningplasma.org/activities/?article=2014%20FESAC%20Strategic%20Planning%20Panel

FESAC Report on Magnetic Fusion Energy Program Priorities (2012)
FESAC Prioritization of Scientific User Facilities during 2014-2024 (2013)
China CFETR Plan (2013)
Fusion Electricity: A roadmap to the realisation of fusion energy (EU, November 2012)
Annexes to Fusion Electricity: A roadmap to the realisation of fusion energy (EU, 2012)
FESAC Fusion Materials Sciences and Technology Opportunities in the ITER Era (2012)
FESAC Opportunities and Modes of International Collaboration During the ITER Era (2012)
Fusion Nuclear Science Pathways Assessment (2011)
Workshop on Opportunities for Plasma Astrophysics report. (2010)
High-Energy-Density Laboratory Plasmas (HEDLP) Basic Needs Workshop Report (2009)
Magnetic Fusion Energy Sciences Research Needs Workshop (ReNeW) Study (2009)
Low Temperature Plasma Science Workshop Report (2008)
FESAC 'Priorities, Gaps and Opportunities' Report (2007)
The National Academics report "Plasma Science: Advancing Knowledge in the National Interest" (2007)
Fusion Simulation Project Research Needs Workshop Report (2007)
Strategic Program Plan for Fusion Energy Sciences (2004)
FESAC A Plan for the Development of Fusion Energy (2003)