Report of the FESAC Facilities Construction Projects Subcommittee

In response to the charge letter from Dr. Asmeret Asefaw Berhe
to the Department of Energy Office of Science Federal Advisory Committees
December 1, 2023

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Executive Summary

Fusion is the ultimate clean, sustainable, carbon-free energy solution for growing U.S. electricity needs. The emergence of a vibrant private fusion industry has reignited public enthusiasm and inspired the 2022 White House Bold Decadal Vision (BDV) to accelerate fusion development. Enthusiasm has further grown with the 2022 and 2023 demonstrations of inertial fusion energy (IFE) scientific gain and the 69 megajoules (MJ) of deuterium (D) – tritium (T) fusion heat released over six seconds at a magnetic confinement facility in the United Kingdom, respectively.

In response to a December 1, 2023 charge letter from Dr. Asmeret Berhe to the Department of Energy (DOE) Office of Science Federal Advisory Committees to assess new or upgraded world-leading facilities over the next decade, a 13-member Subcommittee was established by Fusion Energy Science (FES) and the Fusion Energy Sciences Advisory Committee (FESAC). FES provided an initial list of 10 facilities for evaluation. The Subcommittee solicited community input in a 'dear colleague' email on January 16, 2024. 40 whitepapers were received from the U.S. fusion community. The Subcommittee's assessment of the whitepaper responses involved a minimum facility cost of $100M and resulted in the addition of two new facilities. Thus, the Subcommittee evaluated 12 facilities to support the U.S. fusion community, which included one facility currently under construction, three proposed upgrades to existing facilities, and eight proposed new facilities. A series of public community webinars was held from mid-February until early April 2024, in which speakers were invited by the Subcommittee for each facility, based on whitepaper submissions. The U.S. fusion community was invited to attend these facility descriptions and participate in the question-and-answer period.

The FESAC Long-Range Plan (LRP) has recommended to 'move aggressively toward the deployment of fusion energy' and that 'partnerships will accelerate progress'. Based on these recommendations and the rapid growth of a strong fusion private sector, the Subcommittee, in discussion with Dr. Jean-Paul Allain, the FES Associate Director and the designated federal official (DFO), chose to broaden the definition of question 2a 'potential to contribute to world-leading science' from Dr. Berhe's charge by adding 'and/or close fusion technology gaps'. Further, the Subcommittee chose to categorize which facilities would 'best serve fusion and the BDV'. This assessment was based on: 1) consideration of urgency to provide a decadal impact on the fusion industry and/or fusion science; 2) consistency with the LRP and BDV; 3) answers to questions 2a and 2b from Dr. Berhe's charge; 4) opportunities for partnerships that could accelerate the timeline and/or reduce public costs for a facility; and 5) technology gaps that could be closed by a facility and/or world-leading fusion science.

The Subcommittee developed a strong consensus on four facilities to be included in the 'Best Serves Fusion' category to accelerate the fusion energy timeline and/or provide engineering/ technology experience. These four facilities are largely independent of the fusion plasma core confinement concept and were rated (a) "absolutely central" in response to question 2a without further ranking within this category. These facilities are, in alphabetical order, 1) the blanket component test facility (BCTF) to qualify technologies to extract fusion power and breed fusion fuel; 2) the fuel cycle test facility (FCTF) to qualify technologies to extract the fusion fuel and return it to the fusion core; 3) the fusion prototypic neutron source (FPNS) to qualify materials for use in the extreme nuclear environment of fusion power plants; and 4) ITER to transfer knowledge about fusion facility integration and engineering, and ultimately provide a world-class burning plasma scientific facility. Moreover, the Subcommittee determined that all eight of the remaining facilities evaluated, which largely represent a single pathway to a fusion pilot plant, are (b) important and well-deserving of FES support. Several facilities were assessed to be well suited to leveraging via partnerships. The construction readiness of each facility varied significantly.

This short letter report discusses each of the 12 facilities in response to questions 2a and 2b from Dr. Berhe's charge letter with a brief justification for each categorization. Following Dr. Berhe's guidance, no attempt has been made to rank or order the twelve facilities beyond the identification of four facilities in the 'Best Serves Fusion' category. In the following sections, the facilities are described accordingly in alphabetical order.

Introduction and Process

The mission of the DOE Fusion Energy Sciences (FES) program is to “expand the fundamental understanding of matter at very high temperatures and densities, and build the knowledge needed to develop a fusion energy source” [1]. The Energy Act of 2020 expanded the scientific mission of FES to support “the development of a competitive fusion power industry in the U.S.” [2]. This expansion in mission, combined with the realization that fusion is the ultimate clean, sustainable, carbon-free energy solution for the growing U.S. power needs, has fueled the emergence of a vibrant private fusion industry. The growth of private fusion industry investments has reignited public enthusiasm and inspired the 2022 White House Bold Decadal Vision (BDV) to accelerate fusion development [3]. Public excitement about fusion energy has further grown with the 2022 and 2023 demonstrations of inertial fusion energy (IFE) scientific gain [4] and the 69 megajoules (MJ) of deuterium (D) - tritium (T) fusion heat released over six seconds at a magnetic confinement facility in the United Kingdom [5], respectively.

The recent National Academies of Science, Engineering and Medicine (NASEM) report Bringing Fusion to the U.S. Grid stated ‘urgent investments by DOE and private industry’ are needed, ‘both to resolve the remaining technical and scientific issues, and to design, construct and commission a pilot plant’ [6]. The highly interdisciplinary nature of fusion should ensure that science and technology investments and advances lead to energy on the grid with the potential to impact many scientific and engineering technologies [7]. Thus, fusion is poised to stimulate economic growth, jobs, and innovation in sectors including materials science, nuclear technology, engineering, computer science, and manufacturing.

New fusion facilities addressing critical technology and science gaps are urgently needed for economically attractive fusion energy to help decrease reliance on carbon-based energy sources. A 13-member Subcommittee was established by the DOE FES and the Fusion Energy Sciences Advisory Committee (FESAC) in January 2024 to respond to the charge letter from Dr. Asmeret Asefaw Berhe to the Department of Energy (DOE) Office of Science Federal Advisory Committees that was issued on December 1, 2023. The charge requested that the federal advisory committees “consider what new or upgraded facilities will best serve our needs in the next ten years (2024-2034).” The charge indicated that the subcommittee could add to the list of facilities provided by the Designated Federal Officer (DFO) but should do so only for facilities “that require a minimum investment of $100 million.” Upon finalizing the list of facilities to consider, the charge directed the subcommittee to evaluate, for each project, (a) the potential to contribute to world-leading science in the next decade and b) the readiness for construction.

As directed in the charge letter, the DOE FES provided a list of projects to FESAC, along with their anticipated project cost, or cost range, and status. The full text of the charge letter is provided in Appendix A, in addition to a description of each of the facilities provided by DOE FES and the Fusion DFO, Dr. Jean-Paul Allain.

The Subcommittee consisted of two representatives from the private fusion industry, four university faculty members, and seven representatives from Federally Funded Research & Development Centers (FFRDCs). The list of the Subcommittee members is provided in Appendix B. The Subcommittee issued a call to the fusion community for whitepapers on January 16, 2024, which is provided in Appendix C, and the Subcommittee communicated several times with the fusion community to provide information about the call for whitepapers and the plan for community webinars. In addition to the whitepapers, the Subcommittee was informed in its evaluations and deliberations of fusion research facility priorities by the recent NASEM reports [6,8] and the DOE FESAC Long-Range Plan (LRP) [9]. Additionally, the Subcommittee was informed by the 2023 DOE Office of Fusion Energy Sciences ITER Research Program Research Needs Workshop [10], the 2022 FES Basic

Research Needs Workshop on Inertial Fusion Energy [11], and the 2023 FESAC report on international collaboration [12].

The subcommittee, in consultation with the DFO, defined a process to address conflict of interest (COI), either direct or perceived, due to institutional affiliation in addition to research and service activities associated with an existing or proposed facility. Members with COI did not lead discussions on facilities for which COIs were identified but were able to participate in discussions to clarify issues and provide additional background. The DOE FES DFO was consulted about and approved the approach to COI management. The Subcommittee held numerous virtual meetings to discuss the evaluation process, and later, to discuss and evaluate each facility. In addition, the Subcommittee held a 2-day meeting on April 16-17, 2024, at DOE Germantown headquarters to finalize the evaluations provided in this report. The approach to COI followed by the Subcommittee ensured that all voices were allowed to contribute to a respectful dialogue. This resulted in a well-informed discussion that led to a consensus assessment and report, with a strong consensus on the highest ranked facilities.

In response to the Subcommittee request for whitepapers, forty submissions were received from the U.S. fusion community. These whitepapers provided information relevant to the list of ten facilities provided by DOE FES and proposed several new plasma science or fusion technology facilities. The Subcommittee's assessment of proposed new facilities not on the original FES list involved a minimum facility cost of $100M and resulted in the addition of two new facilities. The Subcommittee did not evaluate facilities with a cost range below $100M; however, a number of these whitepapers proposed less expensive facilities that can positively impact fusion energy and fundamental science and merit future consideration. The call for whitepapers and the full list of whitepapers received are provided in Appendix C. Correspondingly, the following 12 facilities were assessed:

- Blanket Component Test Facility (BCTF)
- DIII-D (eXcite) Upgrade
- Exhaust and Confinement Integration Tokamak Experiment (EXCITE) options (*added by the Subcommittee*)
- Fuel Cycle Test Facility (FCTF)
- Fusion Integration Research and Science Test Facility (FIRST)
- Fusion Prototypic Neutron Source (FPNS)
- High Heat Flux Test Facility (HHF)
- New Inertial Fusion Energy Concepts and Upgrades (*added by the Subcommittee*)
- ITER
- Matter in Extreme Conditions Petawatt Laser Upgrade (MEC-U)
- NSTX-U Liquid Metal/Core Edge Facility (LMCE)
- Midscale Stellarator

These 12 facilities include one facility currently under construction, three proposed upgrades to existing facilities, and eight new facilities proposed to support the U.S. fusion community. It is important to note that the Subcommittee evaluation only considered the proposed upgrades, and not the current programs for the three existing facilities (MEC, DIII-D, and NSTX-U), since the FESAC Decadal Plan Charge Subcommittee will make overall assessments of the existing facilities. A series of public community webinars was held from mid-February until early April 2024, in which speakers were invited by the Subcommittee for each of the 12 evaluated facilities, based on whitepaper submissions. Appendix D provides the schedule of speakers for each of the 12 webinar presentations. Whenever feasible, the Subcommittee identified a speaker to provide a community overview on the proposed facility. For some facilities, the Subcommittee also identified international speakers to discuss international programs and partnership opportunities. The U.S. fusion community was invited to attend and observe these facility webinars and participate in the question-and-answer period.

The FESAC LRP recommended that the U.S. fusion program 'move aggressively toward the deployment of fusion energy' and that 'partnerships will accelerate progress' [9]. Based on these recommendations, and the rapid growth of a strong fusion private sector, the Subcommittee, in discussion with Dr. Jean-Paul Allain, the FES Associate Director and the Subcommittee DFO, chose to broaden the definition of question 2a 'potential to contribute to world-leading science' from Dr. Berhe's charge letter to add '*and/or close fusion technology gaps'*. Thus, we considered question 2a, "*The potential to contribute to world-leading science and/or close fusion technology gaps in the next decade*." The broadened definition of question 2a is consistent with the stated goals of the FES program to: "(1) expand the understanding of matter at very high temperatures and densities, and (2) build the knowledge needed to develop a fusion energy source" [13]. The Subcommittee weighed these objectives equally in evaluating question 2a for each facility.

As well, the Subcommittee chose to categorize which facilities would '*best serve fusion energy/fusion science and the bold decadal vision (BDV)*'. This assessment was based on: 1) consideration of urgency to provide a decadal impact on the fusion industry and/or fusion science; 2) consistency with the LRP and BDV; 3) answers to questions 2a and 2b from Dr. Berhe's charge letter; 4) opportunities for partnerships that could accelerate the timeline and/or reduce public costs for a facility; and 5) technology gaps that could be closed by a facility and/or the ability of the facility to contribute to world-leading fusion-relevant science with each weighted equally. The Subcommittee developed criteria to guide the discussion about each facility and to evaluate the response to questions 2a and 2b from Dr. Berhe's charge, and these criteria are provided in Appendix E.

Several proposed tokamak-based confinement facilities (DIII-D Upgrade, NSTX-U LMCE, EXCITE) address the integrated tokamak exhaust and performance (ITEP) gap explained in the LRP as follows: "High divertor power exhaust solutions need to be integrated with sustainment of high-power density plasma cores, which are needed for generation of significant fusion power. This requires demonstrating integrated strategies for handling exhaust heat fluxes well beyond what is expected in existing devices, while simultaneously supporting sustained high core plasma performance" [9]. As stated in the LRP, "Closing [the ITEP-equivalent] gap is necessary to ensure FPP readiness" [9], although the nature of the ITEP-equivalent gap depends on the proposed FPP concept. As such, the ITEP gap manifests differently for each tokamak approach (e.g., pulsed, steady-state, spherical torus, negative triangularity). Indeed, the equivalent of the ITEP gap must be closed for every magnetic fusion energy (MFE) concept, and the considered Midscale Stellarator facilities also closes ITEP-equivalent gaps.

Each of the facilities evaluated by this Subcommittee are experimental, but it is important to note that advanced high-performance computing (HPC) is essential to accomplishing world-leading fusion science and to close fusion technology gaps to accelerate progress towards a commercial fusion industry. FES has long benefited from both capability and leadership-scale computing facilities provided by the DOE Office of Advanced Scientific Computing Research (ASCR), as identified in the 2019 NASEM report on U.S. Burning Plasma Research [8] and the FESAC LRP [9]. Further, the emergence of Machine Learning/Artificial Intelligence (ML/AI) has tremendous potential for advancing fusion, as discussed in a 2019 DOE FES and ASCR workshop report [14]. Increased access to capacity and leadership scale computing, in addition to the emerging capability of ML/AI-optimized hardware and integrating techniques, are important to fusion and the rapid development of the fusion private sector to accelerate opportunities to realize fusion energy on the grid.

Summary of the Evaluation

The Subcommittee developed a strong consensus on four facilities to be included in the ‘Best Serves Fusion’ category that could contribute to accelerating the fusion energy timeline and/or provide engineering/technology experience. These four facilities are largely independent of the fusion plasma core confinement concept. The Subcommittee rated these four facilities (a) “absolutely central” in response to question 2a) without further ranking within this category. These facilities are, in alphabetical order, 1) the blanket component test facility (BCTF) to qualify technologies to extract fusion power and breed fusion fuel; 2) the fuel cycle test facility (FCTF) to qualify technologies to extract the fusion fuel and return it to the fusion core; 3) the fusion prototypic neutron source (FPNS) to qualify materials for use in the extreme nuclear environment of fusion power plants; and 4) ITER to transfer knowledge about fusion facility integration and engineering, and ultimately provide a world-class burning plasma scientific facility. While ITER is an MFE tokamak facility, the Subcommittee determined that knowledge transfer to the fusion industry about the fusion technology and engineering experience at industrial scale associated with the fusion systems integration and precision engineering, including the lessons learned about quality control, were relevant to all fusion concepts.

The Subcommittee determined that each of the single plasma core concept confinement facilities proposed for closing ITEP-equivalent gaps are (b) important and very well-deserving of FES support. The subcommittee determined these facilities were not (a) ‘absolutely central’ due to their specificity to a single confinement approach to achieving the fusion energy mission. Opportunities to accelerate progress towards closure of significant aspects of the ITEP-equivalent gap exist via public-private partnerships. Private sector confinement facilities planned or under construction will access plasma exhaust regimes to partly close the ITEP gap, and target highly integrated performance to meet stakeholder needs.

The level of readiness for construction varied significantly between all facilities. This short letter report discusses each of the 12 facilities in response to questions 2a and 2b from Dr. Berhe’s charge letter with a brief justification for each categorization, noting responses were not subdivided based on individual white paper submissions or specific concepts for facility implementation. The extent to which partnerships could accelerate construction timeline or reduce public costs is discussed, noting that partnership opportunities, either international or with the private sector, should not be considered obligatory. Following Dr. Berhe’s guidance, no attempt has been made to provide a rank order for the twelve facilities beyond identification of four facilities in the ‘Best Serves Fusion’ category. The facilities in the remainder of this report are described accordingly in alphabetical order.

Facilities that Best Serve Fusion

The following four facilities were found to best serve fusion energy sciences and the bold decadal vision. They are presented in alphabetical order.

Blanket Component Test Facility (BCTF)

Blankets surround the fusing core plasma and play a critical role in both inertial and magnetic fusion energy systems that use deuterium and tritium fuel cycles because they must breed tritium to close the fuel cycle. Blankets must also harness the fusion power by capturing the neutron energy within the blanket coolants, while reducing the neutron and gamma fluxes to sufficiently low values required to shield sensitive components. Blanket research and one or more associated BCTFs are required to provide the scientific understanding and basis to qualify fusion power system blankets for FPP designs and a commercial fusion industry.

Facility description

The BCTF(s) should provide as prototypic and integral of a testing environment as feasible. Options with and without testing in a nuclear environment (e.g., under neutron bombardment and with significant tritium inventory) each have merit and community support. A BCTF should provide flow loops with prototypic breeder and coolant fluids (e.g., PbLi, Li, FLiBe, He, etc.) that connect to scaled first wall and blanket prototypes, which are coupled to a prototypical heat source. The loops provide necessary test beds for the many components and systems that support the blanket, including pumps, heat exchangers, coolant purification systems, tritium (with surrogate deuterium or hydrogen in the non-nuclear BCTF option) extraction systems, diagnostics systems, as well as coatings to control chemistry and inhibit corrosion and tritium permeation.

Building on the US fusion community planning process (CPP) report [15], the FESAC LRP recommended: "Significantly expand blanket and tritium R&D programs" [9]. Moreover the LRP states "Since there is no current path for the US to deploy a test blanket module in ITER, this program should also develop a strategy for component scale blanket testing in a nuclear environment and support preconceptual design and costing studies for facilities such as a blanket component test facility (BCTF), fission irradiations (e.g., HFIR (High-Flux Isotope Reactor at ORNL), ATR (Advanced Test Reactor at INL)), fusion irradiations (e.g., FPNS), and volumetric neutron source (VNS), that accomplish both missions on a time scale necessary to enable the FPP" [9]. Furthermore, the NASEM report states: "A number of different blanket concepts have been proposed and include a variety of solid and liquid blanket configurations to achieve these goals; however, all concepts are at low technology readiness. This low readiness has to be addressed, since the blanket has significant design implications regarding the tritium breeding ratio, power conversion, and maintenance scheme for the pilot plant" [6].

There are potential public-private partnership opportunities for non-nuclear BCTF designs tailored to specific blanket concepts. International collaboration on the UK CHIMERA facility has appeal, noting that (based on information provided in the community webinar) there are no plans for radioactive materials beyond possible trace tritium in CHIMERA. A nuclear-capable BCTF is presently best accomplished via a public sector facility.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(a) absolutely central

The BCTF(s) is/are well-aligned with the recommendations and plans laid out in the CPP, the FESAC LRP, the 2023 NASEM report, and the BDV. The US is not participating in the ITER TBM program, underscoring the need for a dedicated BCTF(s). Moreover BCTF(s) would be of critical importance to advance both MFE and IFE concepts.

Several BCTF concepts were presented and assessed and would make strong contributions to close various technology gaps, depending on details of the design. A flexible, public BCTF and one or more private targeted BCTFs may be needed for timely progress. A public, flexible BCTF would support many users in engineering science. A targeted BCTF would serve to focus effort on R&D questions for specific designs of mutual interest to the public and private sectors. There is a good opportunity for US leadership in a nuclear-capable BCTF, and through collaboration with the UK CHIMERA facility.

Readiness for construction:
(b) significant scientific/engineering challenges to resolve before initiating construction
(for non-nuclear BCTF options with trace tritium)
(c) mission and technical requirements not yet fully defined
(for nuclear-capable BCTF options)

BCTF(s) is a proposed new facility, and there are multiple options based on the breadth of blanket concepts that could be tested in such a facility. Single-purpose, non-nuclear BCTF designs favored by private companies may be more advanced but are not yet ready for construction via a public-private partnership (PPP). However the urgency to advance technology readiness levels (TRLs) underscores the value of a PPP. A design for a multi-purpose, nuclear-capable BCTF has not been initiated, so the engineering questions are not fully identified. One strength in a multi-purpose BCTF is to develop/deploy common elements for various designs.

Fuel Cycle Test Facility (FCTF)

The mission of this facility is to support tritium infrastructure R&D for a fusion pilot plant. This versatile facility will demonstrate fuel cycle technologies at a high TRL level to reduce the risks of unexpected component failures or inadvertent tritium release during fusion plant operation.

Facility description

A Fuel Cycle Test Facility (FCTF) is a single facility, or a group of facilities, focused on the development and testing of fuel cycle technologies and advancing them to a TRL where they can be implemented in a FPP or other fusion plant. Low TRLs can be addressed with protium and deuterium surrogates in a non-radiological facility; however, higher TRLs will require testing with tritium in a radiological facility. To address the technology needs for a FPP, the FCTF will need to be able to handle sufficient tritium and allow for full scale processing rates that are orders of magnitude higher than present state-of-the-art. The facility should be flexible to allow for testing of multiple technologies and subsystems, able to divide and partition tritium inventory between tests on different components and allow access to public and private sectors. The facility can utilize non-radiological (with deuterium and protium) and radiological (with tritium handling) capabilities, ideally co-located and operated by the same team(s). While a non-radiological facility can initially help develop the technology faster, provide training, and operational data, tritium testing will be necessary before operation of a FPP. Due to tritium handling considerations, the FCTF would be best located at a National Laboratory.

The FCTF is closely aligned with the LRP and BDV. The LRP recommends expanding blanket and tritium R&D programs, by developing tritium handling systems (currently not advanced enough for a FPP), and by supporting technologies that minimize the size, cost and tritium inventory of the FPP. Additionally, the NASEM report “Bringing Fusion to the US Grid” [6] specifically recommends establishing and demonstrating efficient tritium processing technologies at relevant rates and processing conditions before operation of a FPP.

A FCTF would close several key gaps on the way to a FPP. These include continuous operation of the tritium processing system and the handling and recovery of tritium within a FPP environment with minimum size and inventory.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(a) absolutely central

While not calling out a FCTF by name, the LRP states that “emphasis is needed on fusion materials science, plasma-facing components, tritium-breeding blanket technology and the tritium fuel cycle" and that "critical enabling technologies such as plasma-facing components, structural and functional materials, and breeding-blanket and tritium-handling systems are not yet advanced enough for an FPP" [9]. The LRP also recommends that we “significantly expand blanket and tritium – R&D programs" [9]. A FCTF is indeed critical for the DT fuel cycle, and all eight companies that received awards through the DOE Milestone program have a DT fuel cycle. As such, there is a need to make progress on the fuel cycle, moving on from ITER know-how to modernize and scale the technology for private sector use. The proposed facility will have more flexibility than ITER to advance TRLs of a burgeoning, diverse, and competitive fusion industry. Based on recent reports and workshops, the facility will support 6 fuel cycle research topics identified by the community: (1) Process Modeling, Process Control, & Simulation; (2) Tritium Inventory Reduction & Improved Process Technologies; (3) Isotope Supply; (4) Tritium Confinement to Reduce Emissions and Tritium Effects on Materials; (5) Tritium Accountability and Tritium Analytical/Diagnostic Capabilities; (6) Fusion Waste, Regulation, Non-Proliferation, Community Engagement. Finally, the facility will address the needs of a broad range of fusion concepts and build the workforce to support industry.

Readiness for construction:
(b) significant scientific/engineering challenges to resolve before initiating construction

The elements needed for the FCTF are well known by the tritium science and fuel cycle community without any significant additional R&D needed to proceed. However, there are engineering challenges with the design of a modular approach to test multiple concepts simultaneously with minimal interruptions to operations. By locating this facility at a National Laboratory, it will be possible to leverage existing experience building and operating facilities used for tritium production. Due to the concern that there will be insufficient tritium available globally to fuel the initial generation of fusion reactors, one could co-locate the FCTF with a tritium-producing fission reactor. Opportunities to collaborate internationally may also accelerate fuel cycle technology although we must simultaneously develop the US capability, workforce and supply chain in this field in part due to export control restrictions. The workforce exists to enable construction, both for the non-radiological and radiological facilities. Construction timing requires management as this workforce also supports large NNSA projects (e.g., production within the nuclear stockpile).

Fusion Prototypic Neutron Source (FPNS)

The scientific and engineering demonstration of fusion energy requires structural and plasma-facing materials with sufficient dimensional stability and resistance to the 14.1 MeV peaked neutron degradation of thermal-mechanical and physical properties. These materials also will need to meet environmental and safety requirements such as low quantities of long-lived radioactivity, low concentrations of short-term volatile radioactive species and modest decay heat [16]. An FPNS will uniquely address the fundamental scientific questions of whether materials retain adequate properties and integrity for damage levels greater than 20–50 displacements per atom (dpa) with a fusion prototypic neutron energy spectrum, as well as explore lifetime limits from an engineering science perspective at higher irradiation exposures. These transmutation reactions induce much higher hydrogen and helium production than what occurs in fission reactors, in addition to the impurities that result as daughter products from these reactions. FPNS will de-risk many materials to be used in a Fusion Pilot Plant and is thus absolutely central to the development of a commercial fusion industry. FPNS will also validate first-principles models and improve scientific understanding of high-energy neutron irradiation of materials in the presence of transmutant elements.

Facility description

Currently there are large knowledge gaps for many proposed fusion materials due to the lack of a relevant testing environment. In 2022, the Electric Power Research Institute (EPRI) hosted a workshop on FPNS performance requirements, resulting in consensus on two operational goals. The first would be at the 5 years post CD-0 with a target of 5-10 dpa/yr (Fe eq.) in > 50 cm^3 and the second at CD 0 +10 years with a target of 15 dpa/yr (Fe eq.) in > 300 cm^3 [16]. An FPNS with these operating parameters would allow for scientific exploration of materials effects from high energy neutrons, validation of models, and the development of engineering design input necessary for a FPP and a commercial fusion industry, regardless of the confinement approach. This information is needed to rapidly develop new materials to support cost effective and safe commercialization. The relevant diagnostic tools and technologies now exist for incorporation into an FPNS that targets small-volume test samples, which differentiates the FPNS from a volume-neutron source. The sixteen concepts submitted to a 2023 FES request for information in Spring 2023 can be categorized as follows: Accelerator driven, laser driven, neutron generator, and DT fusion neutron sources.

The LRP and earlier community reports have repeatedly expressed the need for an FPNS. The LRP specifically states that, “The fusion pilot plant goal requires increased investment in research and development of fusion materials and other critical technology. Emphasis is needed on fusion materials science, plasma-facing components, tritium-breeding blanket technology and the tritium fuel cycle” and that, “The Fusion Prototypic Neutron Source (FPNS) will provide unique material irradiation capabilities” [9]. Supporting the BDV, testing plasma facing and other materials within the neutron flux is essential to ensure the success of a pilot plant that can withstand sustained fusion reactions for long durations. To date, these reactions have only been sustained for seconds to minutes. To put energy on the grid, these materials must withstand months of exposure to this environment. The FPNS is one of the essential facilities needed to make that a reality.

There is currently a large performance knowledge gap for materials in a fusion environment because no relevant fusion neutron testing environment currently exists. An FPNS would allow the following knowledge gaps for all types of materials to be investigated, understood and closed for a fusion relevant environment with 14.1 MeV neutrons: microstructure and phase stability, radiation/neutron embrittlement, transmutation effects and irradiation creep. There is the possibility to collaborate internationally with the IFMIF-DONES effort. However, a US based FPNS facility would provide US leadership and allow the US to host international and private company collaborations and partnerships.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(a) absolutely central

A Fusion Prototypical Neutron Source supports both science and engineering needs for multiple device concepts and will allow the assessment of fundamental science and materials challenges in radiation effects (combined effects). The FPNS will allow the community to rapidly develop and demonstrate materials characteristics and survivability for the following: structural components (first wall, blanket, vacuum vessel), plasma facing components (divertor, first wall, other internal components), functional components (shielding, magnets, cryostats), diagnostics/controls (optical windows, fiber optics, sensors, etc.) and safety components (shielding, tritium systems, fuel handling). In addition, it will enable the development of an engineering design and licensing database which can be utilized by designers and regulators for future fusion energy plants. It will also enable the validation of models, simulations and calculations which are also critical to the design and licensing of a fusion energy plant.

Readiness for construction:
(b) significant scientific/engineering challenges to resolve before initiating construction

FPNS is a proposed new facility, and significant effort has been put into mission requirements definition. In the DOE 413.3b space, a mission need statement is the required next step. Following that, comes an analysis of alternatives, which will narrow down the technology from the 16 proposed concepts. All these concepts require significant risk reduction and development before deployment. There are multiple DOE and non-DOE sites that fit within site selection criteria for housing such a device. Current estimation is that this would be a billion-dollar-class facility in terms of cost.

ITER

ITER is currently under construction in the south of France as a partnership between the European Union, China, India, Japan, Korea, the Russian Federation, and the United States. The U.S. is responsible for approximately 9% of the construction costs and 13% of the cost of operation. When ITER is completed, it will be the world's premier tokamak-based research facility. The primary objective of ITER is to prove the feasibility and control of fusion at a reactor-relevant scale and to produce 500 MW of fusion power during long (400 to 3000 second) plasma durations. ITER will demonstrate the physics of 'burning' plasmas for long durations, i.e., it will achieve self-sufficient and sustained fusion reactions in the fusion plasma without external heating. ITER will also test the availability and integration of multiple technologies required for a fusion reactor. This assessment only covers the decadal time period associated with completing ITER construction and does not consider ITER research operations.

Facility description

The U.S. ITER project completed Energy System Acquisition Board approval of the project execution plan and performance baseline in December 2023 with a total project cost of $6.5B. Participation in both the construction and operation phases of the ITER project will offer opportunities to gain knowledge and experience that can directly contribute to developing fusion as an energy source. Numerous reports over the last 5 years have emphasized the importance of ITER, including the 2019 NASEM Burning Plasma Research report which states that ITER provides "the most cost effective way to gain experience with a burning plasma at the scale of a power plant." [8]. The 2022 FES Research Needs Workshop provides excellent descriptions of the scientific and technology opportunities that ITER will provide [10]. The submitted whitepaper on ITER states that "specific ITER contributions to fusion research and related fusion pilot plant efforts include thermal and energetic particle transport and stability model development and validation in electron heated regimes; scenario development and performance optimization in pulsed and steady-state regimes; power and particle handling together with transient avoidance, mitigation and control in long-pulse metal-walled facilities; long time-scale DT fuel cycle and tritium breeding technology, and the integrative science and technology goals of demonstrating the routine operation and controllability of a high-gain burning plasma at reactor scale" [17].

ITER is well aligned with fusion research priorities and has consistently been recognized within recent NASEM reports [6,8], the DOE FESAC LRP [9], in addition to the 2023 FESAC report on international collaboration [12]. During the construction phase, ITER has already contributed to understanding the scientific basis of fusion energy. In addition, ITER has provided knowledge transfer regarding the fusion technology and engineering experience at industrial scale associated with the fusion systems integration and precision engineering. The anticipation that ITER will be a well-diagnosed burning plasma experiment provides the opportunity for developing substantial scientific understanding of plasma operating scenarios, disruption mitigation techniques, and the technology associated with the tritium fuel cycle and continuous plasma fueling. However, the U.S. is not a participant in the ITER TBM program, and the U.S. will not have the access to the data, engineering and technological expertise gained from the ITER TBM, unless official partnerships are established with current TBM teams.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:

(a) absolutely central

ITER has and will provide knowledge transfer about the integrated engineering experience at industrial scale, including the importance of quality control in precision engineering and assembly. ITER will provide open-access data to partners, and in the operational phase will provide well-diagnosed, long-pulse burning plasma at reactor scale. This will provide the opportunity to develop plasma operation and control scenarios, including disruption mitigation. The resulting data will validate models and understanding of thermal and energetic particle transport and stability in H-mode MFE plasmas. ITER will provide technological experience and expertise with the D-T fuel cycle, tritium handling and continuous plasma fueling. ITER has, and will continue to, provide supply chain and workforce development opportunities. However, the U.S. is not part of the ITER TBM program.

Readiness for construction:
(a) ready to initiate construction

ITER is already under construction, although the project schedule will be re-baselined later in 2024. The re-baselining of the ITER timeline includes a shift to a full tungsten first wall and divertor, the addition of 40 MW of electron cyclotron heating and 10 MW of ion cyclotron heating, along with a shift in the schedule to a more rapid progress towards a D-T operating phase. The schedule and costs associated with the re-baseline are expected to become clearer later in 2024. The U.S. ITER project has delivered 60% of the planned contributions to the ITER project with remaining deliverables including: central solenoid modules and structures (FY25); disruption mitigation (FY26), tokamak cooling system, vacuum auxiliary system, ECH transmission lines & roughing pumps (FY29), tokamak exhaust processing (FY30), pellet injection (FY32), ICH transmission lines (FY33), and diagnostics systems (FY31 & TBD).

Proposed Facilities

The following facilities, presented in alphabetical order, are deemed important and worthy of support by FES.

DIII-D Upgrade

The DIII-D team proposes to address the ITEP gap by upgrading their electron-cyclotron resonance heating (ECH) system to increase the power absorbed by the plasma, in addition to changing out divertor and wall materials. This allows the facility to access conditions where it can test various solutions to the core-edge integration challenge.

Facility description

DIII-D is a midscale, short-pulse tokamak originally built in 1986. It has a large set of diagnostics, advanced control systems, high flexibility with respect to plasma-facing components, and a track record of doing excellent scenario development and science in support of the advanced tokamak and ITER. The DIII-D Upgrade plans to address the core-edge integration challenge by upgrading the electron-cyclotron resonance heating (ECH) system to increase the power injected into the plasma from 4 to 14 MW (translating to a rise in total heating power from 20 MW to 34 MW when a separate NBI upgrade is factored in). This upgrade, combined with the fact that DIII-D will have minimal nuclear activation and therefore be able to change first-wall materials and divertors, will allow the facility to access conditions where it can test various solutions to the core-edge challenge. These include the development and installation of novel divertor designs, and the development of novel operational scenarios, including those relevant for steady-state tokamak. Additionally, the facility would address implementation of novel PFC materials, and the extension of demonstrated operational scenarios to higher performance, e.g., higher temperatures, densities and pressures. The DIII-D Upgrade is an enhancement to an existing facility, while a new confinement facility is required for the EXCITE Options.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

The mission is very well aligned with the BDV and the LRP, where core-edge integration is called out specifically. The DIII-D team is very strong - including collaborators from leading institutions. The device is a very well-diagnosed and well-heated tokamak. The proposed DIII-D upgrade will take advantage of existing infrastructure investment. The proposed ECH upgrade, together with a separately funded upgrade to neutral beam heating, would bring DIII-D from 20 MW to 34 MW – a 70% increase, and a high ratio of power to radius (P/R) of 20 MW/m, which is very competitive worldwide. The P/R metric is used in MFE to quantify the relevance to the heat exhaust challenge for a reactor. Moreover, adding substantial electron heating will make the discharges significantly more reactor-relevant by increasing the ratio of electron to ion temperature and reducing plasma rotation. Also, the heating upgrade would push the pedestal pressure and beta values beyond those of peer facilities, provide access to peeling-limited pedestals, increase density, and increase divertor pressure, albeit not all simultaneously.

Many facilities worldwide compete in this space, some with features going beyond the upgraded DIII-D capability. Also, a number of these devices operate or have operated with more reactor relevant, non-carbon plasma-facing components, whereas this is not yet the case for DIII-D, although plans were presented to change out the first wall. Relative to a reactor-grade plasma, DIII-D, and any other existing tokamak, cannot simultaneously demonstrate high bootstrap fraction, high parallel heat flux$_{\|}$, high core pressure, low pedestal collisionality, and high separatrix pressure. This can only be achieved in a new device. Reactor-relevant core-edge integration solutions should be capable of being maintained stably over long periods of time. DIII-D, being short-pulse, can begin to address these issues but proving stability over long-pulse time scales relevant for a tokamak reactor would require a future device.

Readiness for construction:
(a) Ready to initiate construction

The clear, well-defined, and relatively uncomplicated scope of the proposed upgrade, and the fact that DIII-D has been operating for well over 20 years and has a proven track record of making upgrades to its facility; provides confidence that the facility is indeed ready to initiate construction of the ECH upgrade shortly after securing the necessary funding.

EXCITE (EXhaust and Confinement Integration Tokamak Experiment) Options

The EXhaust and Confinement Integration Tokamak Experiment (EXCITE) Options is a type of proposed tokamak confinement facility whose mission is to resolve the ITEP-equivalent gap. As described in the introduction, the ITEP gap involves integrating a high-performance plasma core with a power exhaust solution. While all EXCITE facility options are tokamaks, the ITEP gap manifests differently for each tokamak approach (i.e., pulsed, steady-state, spherical torus, negative triangularity). Most public and private roadmaps to fusion include an EXCITE-class facility to specifically demonstrate the feasibility of the proposed FPP plasma core concept. For pulsed tokamaks, the ITEP gap is also partially closed by ITER, though at reduced power density. Closure of the ITEP gap does not imply closure of all long-pulse plasma integration challenges, such as long-duration materials degradation.

Facility description

The EXCITE facility options provided in the submitted whitepapers, including submissions from private companies selected for the DOE-FES Milestone PPP program, are all tokamak-based confinement devices with a mission of resolving the ITEP gap. Approaches considered include pulsed tokamaks, steady-state advanced tokamaks, and variants featuring negative triangularity cross-section shaping. All approaches feature a magnetic field higher than what is available in existing devices. A key distinction between the EXCITE Options and the DIII-D upgrade is that a dedicated EXCITE facility should further close the ITEP gap by simultaneous demonstration of key plasma core and edge parameters, such as higher sustained core pressure with higher heat-flux power handling. The extrapolation to an FPP is thus reduced with an EXCITE-class facility, though at the increased effort of a new device.

Both public-sector and private led approaches were proposed and considered. A public-led user facility could design-in additional flexibility to cover a wider range of tokamak approaches and core scenarios and allow the open development of innovative techniques. Private facilities offer the ability to leverage resources beyond DOE-FES and the opportunity to accelerate construction timelines, but generally feature a higher degree of early-stage approach down-selection. One private sector approach is already well into construction (post CD-3 equivalent stage) and proposed public-sector support for facility enhancements as opposed to a new facility. This is a significantly different value proposition than a fully new confinement device though with reduced flexibility due, in part, to potential nuclear activation resulting from DT operations. In the coming years, other private-led EXCITE-class facilities may also initiate construction using the tokamak or another plasma confinement concept. We note the relevance of closing the ITEP-equivalent gap for MFE concepts beyond the tokamak.

Closure of the ITEP gap via an EXCITE facility was centrally highlighted in the LRP [9], and associated CPP [15], as well as the NASEM Burning Plasma report [6]. In the LRP, the initiation of the conceptual design for EXCITE was recommended for all budget scenarios. The BDV calls for private sector actors to lead concept-specific EXCITE-class facilities to retire physics risks prior to embarking on their specific FPP vision.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

Closing the ITEP gap is central to the extrapolation of the tokamak concept to reactor scale and to build confidence towards a tokamak based FPP. The EXCITE Options provide the highest fidelity platform to close the ITEP gap, though at a significantly higher cost than existing facility upgrade options if not significantly leveraged by private sector partnerships. We note that ITEP-equivalent gaps also exist for other confinement concepts, and that closing the ITEP-equivalent gap is a necessary step on the critical path to an FPP for any MFE-based fusion roadmap. While closing the ITEP-equivalent gap is central to MFE, EXCITE is rated as important as the facility primarily addresses a tokamak-specific mission and does not close gaps beyond this configuration.

Readiness for construction:
(b) significant scientific/engineering challenges to resolve before initiating construction

Despite being a priority of the LRP, the proposed public-led facilities have not matured a specific point design consistent with engineering pre-conceptual design, nor matured an EXCITE facility option to the point of readiness to initiate construction. No mapping of a pre-conceptual design to a facility cost or construction timeline was provided. While the committee does not believe there are significant technological gaps that must be closed prior to initiating facility design and construction, up-front decisions (such as plasma-facing materials choice) may need to be taken which would ultimately reduce flexibility. With the addition of private investment, EXCITE facility options could be brought to readiness for construction relatively rapidly. The workforce needed for construction exists, and the private sector is already embarking on the construction of EXCITE-class facilities to close the ITEP gap for specific approaches.

Opportunities to accelerate progress towards closure of significant aspects of the ITEP gap exist via public-private partnership, potentially fulfilling the EXCITE facility mission as laid out in the FESAC LRP.

Fusion Integration Research and Science Test Facility (FIRST)

The FIRST project is envisioned as a nuclear technology test facility, which integrates the combined effects of neutron damage from 14.1 MeV neutrons, fully operational blankets and their associated subsystems, and an at-scale fuel cycle. The committee was asked to evaluate a single FIRST facility in the context of being an alternative for individual single purpose test facilities (e.g., FPNS, BCTF, FCTF, HHF) to leverage economies of scale. In addition, an integrated facility can elucidate behavior and issues that may not be evaluated in single-effects test stands. Exposure to DT fusion neutrons will address materials science, degradation, and performance issues. The blanket will operate under nuclear conditions to test tritium breeding, shielding, and thermal management with at-scale complex structures and coolants under prototypic conditions of temperature, pressure, magnetic field, and mechanical stress. FIRST will also allow for the testing of all aspects of the fuel cycle systems and technologies including separating hydrogenic species from plasma exhaust impurities and the various blanket concepts, isotopic separation of hydrogen isotopes, and then providing the D-T fuel back into the fusion device. In addition, the facility would generate neutrons from a plasma core that could be a torus-based fusion configuration (e.g. tokamak or spherical tokamak) or non-torus (mirror, FRC, inertial fusion-based). With a nominal plasma core, additional gaps on plasma sustainment and core-edge under burning plasma conditions could be used in an integrated design for accelerating development of fusion energy.

Facility description

The physical phenomena that FIRST would investigate would aim to replace the need for single-effects facilities such as the FPNS, VNS, HHF, BCTF, and FCTF facilities. Doing so requires an intense plasma source that produces a significant and sustained neutron flux. The aim to use FIRST to investigate damage from fusion neutrons establishes it, in essence, as a highly available fusion power plant without the requirement to produce electricity.

A public FIRST facility should address the needs of a broad community of users; however, such an integrated facility requires a down selection of technologies to enable operations and control costs. For example, the selected plasma core may significantly impact the choice of possible blankets, which will influence the scope of the tritium extraction facility and other tritium systems. Similarly, a FIRST facility may be constrained in how it could assess the wide range of blanket, heating conditions, and fuel cycle configurations relevant to many fusion concepts.

FIRST is not called out directly in the LRP and BDV. However, FIRST would significantly address a substantial number of the objectives put forward in the LRP and BDV. The subcommittee views that a public led FIRST is not consistent with a decadal time frame.

Five whitepapers offered options and considerations for a FIRST facility: 1) Use a tokamak as the plasma source with the acknowledgment that a versatile blanket and fuel cycle design will be challenging; 2) Use FIRST to bridge ITER and FPP. A separate BCTF would be required due to the disparate nature of blankets; 3) Use a magnetic mirror as a FIRST facility; 4) Use a laser driven fusion facility as FIRST;5) Build several separate-effect test stands to investigate HHF, FPNS, BCTF, FCTF issues. Private fusion devices would demonstrate integrated effects, and public support could provide public access to some of that data.

FIRST is not a new concept: Former US design studies, such as the Fusion Nuclear Science Facility [18] underwent significant investigation and share many common aspects of FIRST. ITER, while not emphasizing technology development or flexibility, will fulfill some integration aspects described above, as will the UKAEA STEP facility [19]. In our present environment, nearly every private fusion concept calls for an integrated facility of their own design that could meet many aspects of FIRST.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

Integrated testing in a nuclear fusion pilot plant is critically important to resolve science and technology gaps prior to a commercial fusion industry. Nevertheless, to rapidly accelerate towards a FPP, the single purpose facilities (e.g., FPNS, BCTF, FCTF, HHF) were deemed more achievable on a rapid time scale and have much broader applicability than a FIRST facility, although leaving a risk associated with integration. The importance of FIRST is demonstrated by the proposition that each private fusion company plans to construct an integrated facility of their own design. Private fusion companies can anticipate the same challenges with integrated nuclear technology and performance that a public FIRST facility would face, but the private sector may be more tolerant of risks. FIRST-type facilities will be built by private companies; whether there is a public benefit depends on whether public funding is provided.

Readiness for construction:
(c) mission and technical requirements not yet fully defined

Due to the highly integrated nature of FIRST, construction of this facility requires data from blanket, fuel cycle, heat flux, neutron damage studies to de-risk numerous aspects of the facility. A FIRST that bypasses single-test facilities puts excessive risk on facility readiness for construction. Furthermore, an integrated facility requires a down selection of a fusion core, which may limit some aspects of its versatility and applicability to a broad community of users.

Many privately funded confinement devices plan to progress towards an FPP with aggressive timelines. While facing the same integration challenges as public facilities, private facilities will likely have a higher tolerance for risk. Privately funded, publicly supported FIRST-type facilities could provide integrated testing across multiple fusion concepts. That has the potential to accelerate readiness for construction and decrease public cost. Public support of *multiple* sufficiently mature private concepts (e.g., through the Milestone program) could result in several (e.g., tokamak, stellarator, ICF, mirror) FIRST-type integration facilities that could be made available for public technology development and integration testing.

High Heat Flux Test Facility (HHF)

Plasma facing components (PFCs) are critical elements for all fusion reactor concepts, especially magnetic fusion energy (MFE) concepts. Immediately adjacent to the fusion plasmas, these solid or liquid plasma facing materials (PFMs) must survive high heat fluxes without negatively impacting the fusion reactions and reactor lifetime. Due to the diversity of heat load requirements, multi-scale and modular HHF testing provides the most cost and time efficient advancement of PFM. This includes coupon testing (cm scale), non-nuclear component testing (tens of cm to meters scale), and nuclear component testing. Dedicated HHF testing at coupon, component, and nuclear component scales enables higher understanding of response, capability margins, and performance risk.

Facility description

The High Heat Flux Test Facility (HHF) is a facility to expose coupon and/or component sized materials (such as PFCs and PFM's) to FPP-relevant surface heat loads. The surface level heating may be driven by a single heating source or by a combination of plasmas, lasers, or electron beams or through thermal radiation. The facility capabilities will incorporate both steady state and transient heat loads with integrated cooling capacity. Testing of neutron irradiated materials (also called nuclear testing below) is an option and can be leveraged as a phased enhancement of a component HHF. The UKAEA CHIMERA facility is under construction for multi-effects component testing, including thermal radiation HHF testing with applied magnetic fields and water cooling. Upgrade plans for CHIMERA include the addition of a HHF laser source and PbLi loops.

The LRP states that "testing capabilities to explore properties of materials and plasma-facing components, both solid and liquid, under high heat fluxes address a key gap toward FPP material definitions…The coupon level testing is a prerequisite for component-level testing (tens of centimeters to meters scale) to qualify components for an FPP. Accordingly, testing facilities for both levels of high-heat-flux materials research are required" [9]. The NASEM report cites challenges with HHF in high power density, compact fusion systems as 1) excessive heat flux at the divertor plate, and 2) transient heat flux including those due to edge localized modes (ELMs) [6]. The NASEM report recommends that DOE support a research program and new facilities, (including linear devices) for testing PFCs and non-plasma heat flux testing platforms, to identify, evaluate, and finalize a high-confidence, robust design for PFC and first wall armor materials, including both solid and liquid metal options, that are compatible with managing steady state and transient power loading [6]. Sophisticated material development with validated response modeling provided by HHF testing can be pursued in parallel to accelerate system level fusion energy development.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:

(b) important

Although there are a handful of coupon-level HHF test facilities in the U.S., the large majority of HHF testing capability is outside of the United States. The development of additional domestic coupon and component HHF testing in the US would accelerate the scientific basis and certification of PFCs due to increased throughput and could be accomplished through both public and private facilities. These considerations, along with the opportunity to advance PFC armor development through small-scale component testing in less expensive facilities, contributed to the Subcommittee evaluation (of important) for the HHF facility. However, we note that testing capability for both solid and liquid PFCs is an important need, and urgency exists for additional HHF domestic facilities due to the aggressive private timelines of fusion pilot plants, and the need to develop and validate materials prior to system level reactor testing. Nuclear HHF component testing is important for PFC certification and may be leveraged as a phased enhancement which would be world leading.

Readiness for construction:
(a) ready to initiate construction

Detailed design and reviews have not been completed for a proposed domestic facility that would incorporate nuclear HHF testing. However, HHF technology is at a high TRL as evidenced by the existing international facilities. HHF facilities could include the option to build multiple test stands in a single integrated facility or be paired with blanket component testing facilities. For example, the multi-effects testing UKAEA facility CHIMERA is presently under construction and offers partnership potential. Further, it is noteworthy and greatly beneficial that non-nuclear HHF testing capabilities at small coupon scale and intermediate component scale are readily available at capital investment costs well less than $100M, allowing for an assessment of ready to initiate construction, complemented by the international facility experience. In order to achieve BDV timelines, utilization of such low-cost coupon level testing facilities that are ready to initiate construction is ideal. These facilities can be updated or enhanced in the future to include component level and nuclear testing.

New Inertial Fusion Energy Concepts and Upgrades

The mission of this facility is to advance the understanding and TRLs of several critical aspects of laser-based inertial fusion energy reactors. The different concepts aim to bring IFE systems closer to a deployable status in pursuit of the development of an IFE-based FPP.

Facility description

While IFE shares several engineering challenges with MFE, most importantly as it relates to blanket concept testing and a closed fuel cycle facility, it presents a set of obstacles that are specific to laser-driven inertial fusion concepts. The construction of a modular inertial fusion systems facility is essential to address these IFE-specific challenges as well as to develop sound and robust engineering practices for designing future inertial fusion energy pilot plants. A new IFE facility would be instrumental in addressing the enormous engineering challenges associated with long term high-power laser operation, target injection systems for high-repetition rates, fusion chamber material degradation under pulsed irradiation environments, and general systems integration. A new facility could be built in a modular fashion, so that different engineering systems can be studied and tested in a controlled way, and could leverage the important and extensive know-how acquired during experimental ICF campaigns to date.

This facility is viewed as a precursor to an inertial fusion energy pilot plant and would include the development of a kJ-class IFE laser beamline to act as a testbed for R&D to advance a future FPP. The facility will be able to support sub-systems necessary for an IFE FPP demonstration, such as multiple target chambers, target injection and tracking, diagnostics, first wall protection studies, laser propagation through a complex hot environment and optics capable of resisting continuous high fluences. In the short term, the facility will focus on technology development and testing relevant for an IFE FPP. Additionally, calls for upgrades to existing public high-power laser facilities would extend current capabilities for IFE-related science by expanded research capabilities, an enhanced operational availability, and workforce development.

The LRP mentions "the enormous progress made with indirect drive at the National Ignition Facility" [9], and recognizes indirect drive, direct drive, magnetic drive inertial confinement fusion (ICF), and heavy ion fusion as the underpinnings of a viable future IFE pilot plant. The LRP calls for an IFE program that leverages US leadership and current investments to maintain US leadership in ICF and IFE [9]. Additionally, the LRP includes a recommendation to "pursue the development of a multi-petawatt laser facility and a high-repetition-rate high-intensity laser facility" [9]. However, the context within which the LRP considers IFE has drastically changed due to the achievement of scientific gain in IFE [4] and the emergence of a robust private sector (consisting of multiple companies exploring different concepts). Thus, some of the premises of the LRP need revisiting. This has been substantively captured in the DOE/FES Basic Research Needs report in 2022 [11], which provides a TRL assessment of the various systems of an IFE FPP, as well as recommendations to pursue the development of an IFE FPP. The 2023 NASEM HED report [20] also calls for a redoubling of the efforts to achieve ignition and maximum yield. In addition, IFE is part of the BDV and Milestone programs (through engagement with two private IFE companies).

These facilities would address gaps related to critical target physics, such as laser-matter interaction mechanisms during laser-induced target implosion (including but not limited to EOS studies for ultrahigh pressure conditions) and target injection systems for nominal 10-Hz laser shot operation, including direct and indirect drive. Additionally, it would address aspects of the behavior of reactor chamber materials exposed to fusion energy neutrons and (indirect drive), heavy ion exposure, X-ray irradiation, and energy driver technology and laser performance in reactor-relevant environments.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

The development of a modular IFE concept supported by upgrades in current high-power laser facilities would be considered as an important element of the US Fusion Energy portfolio. The US is currently a leader in ICF/IFE, and investments in this area would cement that leadership. The IFE field and its funding landscape are evolving very rapidly, and at present no concepts exist with sufficient technical/engineering maturity to commit to a large integrated facility development project. Now, thus, defining the engineering basis for such a facility through testing of modules of an IFE FPP is considered important.

Readiness for construction:
(c) mission and technical requirements not yet fully defined

In the context of a rapidly evolving IFE R&D landscape, with several concepts being considered and fast progress being made, a modular IFE facility does not yet have mission and technical requirements defined. However, given the potential for leveraging private (multiple IFE companies) and public (several Offices) sector resources, as well as rapid technological developments in the field, conditions for an accelerated transition to (b) status in upcoming years can be envisioned.

Matter in Extreme Conditions Petawatt Laser Upgrade (MEC-U)

The Matter in Extreme Conditions (MEC) instrument at the Linac Coherent Light Source (LCLS) is a DOE user facility that combines high power laser-matter interaction experimental capability with the diagnostic power of an LCLS hard X-ray beamline. The MEC-U project is an upgrade, which will significantly increase the power of the high intensity laser system to the petawatt class, increase the energy of the shock-driver laser to hundreds of Joules, and expand the capabilities of the MEC instrument to support groundbreaking studies of matter under extreme energy and density conditions.

Facility description

The MEC-U Project will build a world-leading facility for high energy density (HED) science at the LCLS X-Ray Free Electron Laser (XFEL). MEC-U is a collaboration between the Stanford Linear Accelerator Center (SLAC), the Lawrence Livermore National Laboratory (LLNL), and the University of Rochester Laboratory for Laser Energetics (LLE).

MEC-U will be unique among existing and planned experimental facilities by combining hard X-rays from the LCLS, a kilojoule long-pulse laser, and a state-of-the-art 10 Hz petawatt laser in a flexible experimental platform. The long pulse laser will be an order of magnitude higher energy than at any US or international X-ray light source today. The short pulse laser will be the highest power laser at any X-ray light source, with an IFE-relevant repetition-rate that enables sufficient signal from low cross-section events.

MEC-U will advance the fundamental science of matter at extreme temperatures and densities and can inform several important aspects of IFE technology development. The project will address three priority drivers in plasma science and technology identified in the LRP: “Understand the plasma universe”, “Strengthen the foundations”, and “Create transformative technologies.” In the fields of astrophysical and HED plasmas, high-precision data from MEC-U will enable model validation for multiple important scientific questions, including plasma turbulence, magnetic field amplification (the dynamo effect), and particle acceleration in cosmic and solar plasmas. The IFE-specific advancements offered by MEC-U include (i) achieving relevant parameter spaces for target ablators, (ii) studying laser coupling at high intensities, (iii) testing materials for radiation damage, and (iv) gaining experience with high (10 Hz) rep rate experiments and laser operations.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

As a DOE user facility, the current MEC instrument has been highly scientifically productive, generating groundbreaking research in HED science through user experiments, with over 125 peer-reviewed publications and >2700 total citations. It is expected that MEC-U will build on this success by increasing the number of users 3-4 times and substantially expanding the capacity for delivering high data volume. The MEC-U project also plans to dedicate 50% of accepted future proposals to be IFE-relevant. The run time solicitation is open to academic institutions, national labs, fusion industries, and international partners. Thus, it is expected that MEC-U can enable a broad range of workforce training and development opportunities essential for IFE, both in the public and private sectors. While the MEC-U is an impressive facility to conduct world-leading discovery science, the Subcommittee recognizes that closing gaps in IFE science and technology would be better suited to an IFE development facility.

Readiness for construction:
(a) ready to initiate construction

DOE approved CD-1 for the MEC-U project conceptual design and cost range of $264–461M in October 2021. Project baseline (CD-2) is planned for FY26, and under a technically driven schedule, the MEC-U project can deliver early completion of CD-4 in FY2029. The Project engages in regular reviews and meetings with external advisory committees for user engagement, technical systems, and project management.

Since MEC-U will create synergies across the field of astrophysics, fusion energy, and materials science, the project can address key needs of several other DOE offices and federal agencies. MEC-U will offer broad capabilities for generation and measurement of the precision dynamics of materials, which will address major capability gaps in the technical missions across BES NNSA, NSF, and NASA.

NSTX-U Liquid Metal/Core Edge Facility (NSTX-U LMCE)

The NSTX-U LMCE project aims to advance the understanding and development of presently low TRL liquid metal (LM) plasma-facing components (PFCs) that potentially extend PFC lifetime and optimize the plasma edge for high core plasma performance. The PFCs will face extreme challenges in a compact, high-power density FPP and must be designed to withstand high heat and particle fluxes for a sufficient period of time without failure. Innovation is required as it is unlikely that existing solid materials will provide adequate PFC system performance. LM PFC approaches may provide an alternate solution that affects achievable reactor size, economics and reliability. Testing LM divertors in a tokamak will enable studies of core-edge integration approaches (partially addressing the ITEP gap) and identify the edge lithium concentration where plasma performance is affected.

Facility description
Leveraging the capabilities of NSTX-U, the proposed NSTX-U LMCE will evaluate liquid lithium PFC concepts and study impact on the edge and core plasma. The LMCE upgrade would require replacement of all carbon PFCs with FPP-relevant high-Z material for LM compatibility. LMCE would achieve LM-compatible temperature control using hot helium gas and a bakeout system and will have extensive diagnostics to measure LM properties, transport and effects. NSTX-U LMCE would test a range of lithium divertor concepts. Existing and new preparatory facilities would be needed to reduce risk of failure before installation in NSTX-U. This includes testing full sectors with significant volumes of fast-flowing Li systems, heat sources and magnetic fields. Test stand magnetic fields with permanent magnets could match NSTX-U parameters, but higher magnetic field could help reliably extrapolate to reactor regimes.

NSTX-U LMCE contributes to the LRP emphasis and recommendation to “Strengthen the innovative and transformative research program elements that offer promising future opportunities for fusion energy commercialization” [9]. It contributes to the NASEM recommendation to support studies of the compatibility of innovative divertor designs [6]. LMCE results are of interest to a Milestone program company and several other private fusion companies, and results could be obtained within a decadal timeline.

NSTX-U LMCE aims to raise the TRL of LM systems by understanding material compatibility, stable flows and operational temperature windows. Results could be applicable in multiple magnetic confinement configurations. General physics insights include the ability of a lithium divertor to handle high heat flux and achieve detachment; lithium recycling and retention in the divertor; retention of hydrogen and impurities by lithium; impurity content in the scrape-off-layer (SOL); and potential improvement to core energy confinement. Additional technology challenges, many of which are shared with LM blanket technology, include closed loop lithium handling and procedures at a moderate scale. Implications of LM PFCs should be considered in a Fuel Cycle Test Facility.

Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

NSTX-U LMCE would be unique in the international landscape [12]. The project would drive development of novel LM PFC technology and evaluate viability of LM for managing heat flux, enhancing energy confinement, and improving overall plasma performance. It would provide validation data at controlled surface temperatures for global material migration models, with LM offering a potential solution to complications from large masses of plasma-eroded solid PFC material. However, longer time-scale thermal management would not be studied. In addition, studying the effects of cyclic heat loads and many technology challenges would not necessarily require a tokamak. Rapid development would be necessary for implementation in initial phases of an FPP. Nevertheless, LM PFCs have potential to impact longer term optimization and commercialization and are well-suited for public-program-driven development.

Readiness for construction:
(b) significant scientific/engineering challenges to resolve before initiating construction

Funding is required to support the project development and preconceptual design activities, but preliminary scope, project schedule, cost estimates, and top-level risk categories and mitigation strategies have been identified. Analysis performed for the NSTX-U Recovery project can be leveraged in re-designing NSTX-U to accommodate a range of LM divertor concepts. NSTX-U is currently obligated to complete its primary Research Objectives, and the stated timeline includes NSTX-U operation beginning in Nov. 2025 (early finish), putting the first LM divertor experiments at 2027-2028 for small inserts, and 2029 for broader divertor coverage. The LMCE assessment assumes successful NSTX-U recovery, timeline, and operation, and represents a technical risk. Private sector engagement would contribute to and benefit from this facility.

Midscale Stellarator

A new mid-size stellarator facility would retire risks and innovate towards a high performance, economically attractive, stellarator FPP and could address many of the issues in the ITEP-equivalent gap for stellarators achieving a high-power density plasma core and high divertor power exhaust solution. A midscale stellarator facility would serve as a MFE alternative to the tokamak as it is intrinsically steady-state, disruption-free, and requires low-recirculating power. In addition, high density and benign heat loads are naturally achieved and stellarator operation is largely dictated by external control. Recent advances in the theory and simulation of stellarators and advanced manufacturing techniques motivate renewed interest in this facility. Interest is further evidenced by the large number of private sector entities pursuing the stellarator concept. A mid-scale stellarator facility would give confidence that it is possible to extrapolate this concept to a FPP without the risks associated with runaway electrons and other damaging events associated with the strong parallel plasma currents typical in tokamaks.

Facility description

The U.S. has historically taken leadership in quasisymmetric stellarators and is world-leading in stellarator theory. A U.S-based midscale optimized stellarator would utilize recent theory, modeling and manufacturing advances to cover new ground not accessible on existing devices and complement international collaboration on the quasi-isodynamic W7-X stellarator in Germany, with the Japanese LHD heliotron soon finishing its operations. Two midscale optimized stellarator options were presented to the committee: a DOE constructed user facility at a university or a national lab, and a facility in partnership with the private sector, with public investment in facility and diagnostics enhancements.

The midscale stellarator was described in the LRP as a key facility alternative to the tokamak approach [9]. Since the LRP, significant advances in theory and modeling have enabled the design of experiments with superior optimization properties compared to existing devices. Magnet technology has seen significant advancement over the last several years with the introduction of high temperature superconductors (HTS) and magnetic field flexibility offered by the recent development of planar coil technology. Algorithms have been developed which significantly relax the stringent engineering accuracy requirements and improve the manufacturability of stellarator coils. Additionally, several private stellarator companies have been created, including three in the U.S., two of which are DOE Milestone Program awardees.

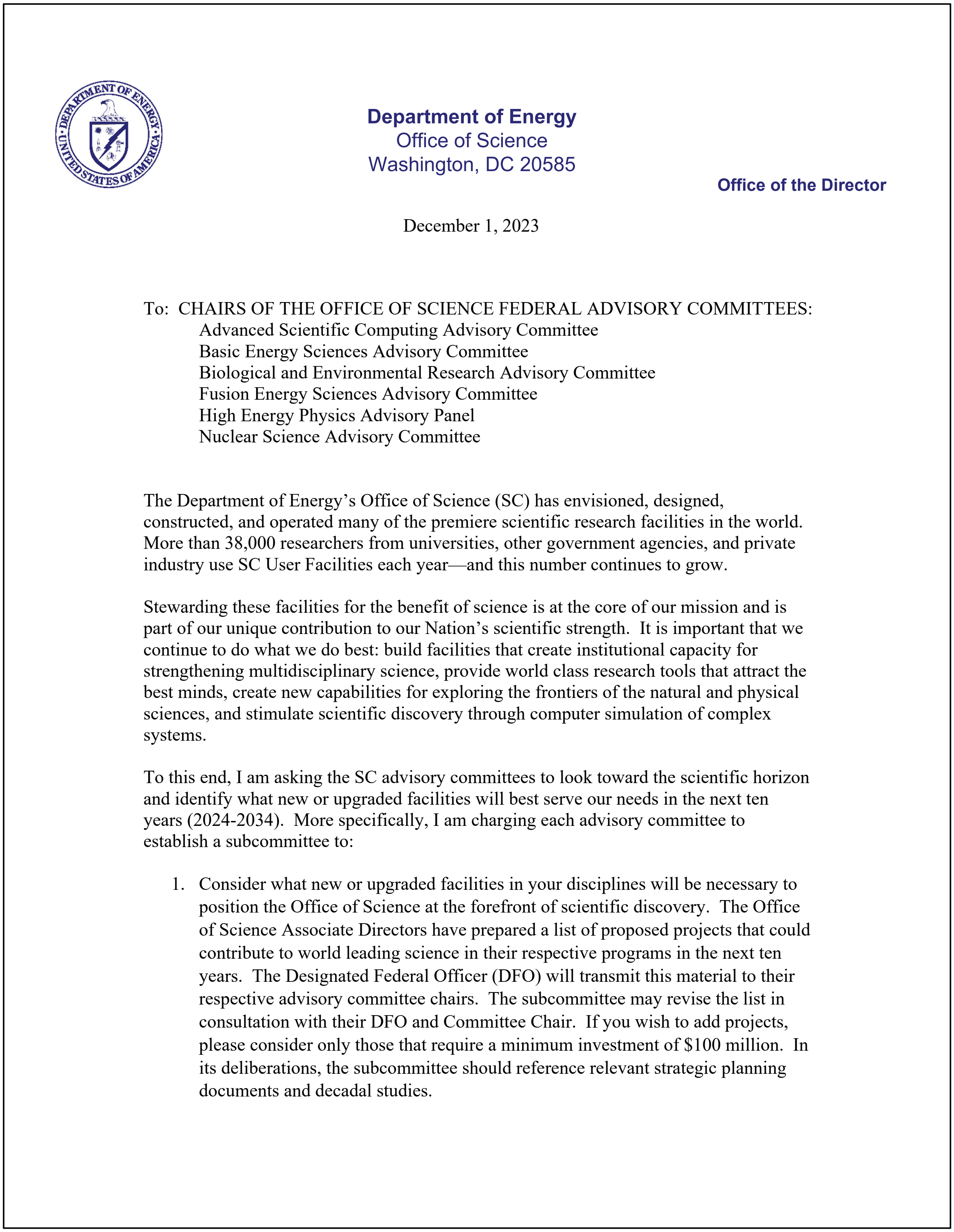
Potential to contribute to world-leading science and/or close fusion technology gaps in the next decade:
(b) important

A midscale stellarator would contribute to world leading fusion science by testing unique optimized stellarator configurations at high temperature and low collisionality, which is relevant for an FPP. The facility would also address many of the issues in the ITEP-equivalent gap from the LRP for stellarators. It would study thermal and energetic particle turbulence in a 3D geometry with innovative divertors that are resilient to changes in the plasma core in a different operating space from tokamaks. A midscale stellarator would demonstrate reduced turbulent transport and energetic particle losses and control while maintaining favorable neoclassical confinement. MHD stability and equilibrium robustness at high beta would also be investigated. This stellarator would utilize new coil simplification design tools and manufacturing for fidelity and timeliness. Also, it would contribute to general MFE knowledge in turbulence, plasma model validation, plasma-material interactions, MHD, energetic particles and other physics as well as MFE technology with possible new magnet development. While closing the ITEP-equivalent gap is central to MFE, a midscale stellarator primarily addresses a stellarator-specific mission and does not close gaps beyond this configuration.

Readiness for construction:
(b) significant scientific/engineering challenges to resolve before initiating construction

A new facility is needed to experimentally evaluate the merits of new stellarator optimizations, possibly including quasi-symmetry, and to explore innovative divertor concepts. Two stellarator facility modalities have been proposed, one of which is a PPP. Community consensus on many of the characteristics of such a facility have been reached but further discussion and possibly scientific/engineering development is required on some key features of this facility as well as further cost analysis. Opportunities exist to leverage private-sector investment in a midscale stellarator facility to extrapolate this concept of a FPP.

Appendix A: Charge Letter and FES Facilities List



Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

December 1, 2023

To: CHAIRS OF THE OFFICE OF SCIENCE FEDERAL ADVISORY COMMITTEES:
Advanced Scientific Computing Advisory Committee
Basic Energy Sciences Advisory Committee
Biological and Environmental Research Advisory Committee
Fusion Energy Sciences Advisory Committee
High Energy Physics Advisory Panel
Nuclear Science Advisory Committee

The Department of Energy's Office of Science (SC) has envisioned, designed, constructed, and operated many of the premiere scientific research facilities in the world. More than 38,000 researchers from universities, other government agencies, and private industry use SC User Facilities each year—and this number continues to grow.

Stewarding these facilities for the benefit of science is at the core of our mission and is part of our unique contribution to our Nation's scientific strength. It is important that we continue to do what we do best: build facilities that create institutional capacity for strengthening multidisciplinary science, provide world class research tools that attract the best minds, create new capabilities for exploring the frontiers of the natural and physical sciences, and stimulate scientific discovery through computer simulation of complex systems.

To this end, I am asking the SC advisory committees to look toward the scientific horizon and identify what new or upgraded facilities will best serve our needs in the next ten years (2024-2034). More specifically, I am charging each advisory committee to establish a subcommittee to:

1. Consider what new or upgraded facilities in your disciplines will be necessary to position the Office of Science at the forefront of scientific discovery. The Office of Science Associate Directors have prepared a list of proposed projects that could contribute to world leading science in their respective programs in the next ten years. The Designated Federal Officer (DFO) will transmit this material to their respective advisory committee chairs. The subcommittee may revise the list in consultation with their DFO and Committee Chair. If you wish to add projects, please consider only those that require a minimum investment of $100 million. In its deliberations, the subcommittee should reference relevant strategic planning documents and decadal studies.

2. Deliver a short letter report that discusses each of these facilities in terms of the two criteria below and provide a short justification for the categorization, but do not rank order them:

   a. **The potential to contribute to world-leading science in the next decade.** For each proposed facility/upgrade consider, for example, the extent to which it would answer the most important scientific questions; whether there are other ways or other facilities that would be able to answer these questions; whether the facility would contribute to many or few areas of research and especially whether the facility will address needs of the broad community of users including those whose research is supported by other Federal agencies; whether construction of the facility will create new synergies within a field or among fields of research; and what level of demand exists within the (sometimes many) scientific communities that use the facility. **Please place each facility or upgrade in one of four categories: (a) absolutely central; (b) important; (c) lower priority; or (d) don't know enough yet.**

   b. **The readiness for construction**. For proposed facilities and major upgrades, please consider, for example, whether the concept of the facility has been formally studied; the level of confidence that the technical challenges involved in building the facility can be met; the sufficiency of R&D performed to date to assure technical feasibility of the facility; the extent to which the cost to build and operate the facility is understood; and site infrastructure readiness. **Please place each facility in one of three categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; or (c) mission and technical requirements not yet fully defined.**

Many additional criteria, such as expected funding levels, are important when considering a possible portfolio of future facilities, however, for this assessment I ask that you focus your report on the two criteria discussed above.

I look forward to hearing your findings and thank you for your help with this important task. I appreciate receiving your final report by May 2024.

Sincerely,

Asmeret Asefaw Berhe

Asmeret Asefaw Berhe
Director, Office of Science

2023 Fusion Energy Sciences Advisory Committee Facilities Charge

In response to Dr. Berhe's December 2023 Facilities Charge, Fusion Energy Sciences is providing the following list of projects for consideration by the subcommittee.

ITER
Total Project Cost (TPC) = $6.5B, FY38 is final funding year

ITER is an international collaboration among seven members as defined in the ITER Joint Implementation Agreement (JIA), namely the European Union, India, Japan, Korea, China, Russia, and the United States. ITER will be a burning plasma fusion device, designed and built to address the principal remaining scientific uncertainty in fusion energy research: the understanding, control, and predictability of a steady-state burning plasma at power plant scale, as well as addressing the associated technologies required to sustain such a device. The U.S. Contributions to ITER consist of approximately 9.09% of the overall project costs, made up of in-kind hardware contributions as well as cash contributions to fund the ITER Organization to support design, assembly, and management of the project. U.S. ITER Project Office (IPO) is located at Oak Ridge National Laboratory, ITER is sited in Saint Paul les Durance, France. ITER is post CD-2/3 for first plasma scope and is pursuing CD-2/3 (ESAAB held December 2023) for remaining scope, Line-item funded.

Matter in Extreme Conditions Petawatt Laser Upgrade (MEC-U)
Total Project Cost (TPC) range of $264M to $461M

MEC-U will provide an internationally preeminent combination of high-energy lasers and high repetition rate, high peak- and average-power lasers with the LCLS XFEL. The MEC-U will have the ability to simultaneously prepare and probe a wide range of targets at extreme field strengths, plasma densities, pressures, and temperatures at a repetition rate that will enable very high productivity scientific output of relevance to High Energy Density Science and inertial fusion energy. The facility will have the ability to study the dynamics of relativistic plasmas and precision material properties and create and study powerful high-flux secondary particle sources. MEC-U will be located at SLAC to allow for coupling with the LCLS XFEL. MEC-U received CD-1 on October 4, 2021.

Fusion Prototypic Neutron Source (FPNS)
Total Project Cost (TPC) range of $200M-$2.5B

The scientific and engineering demonstration of fusion energy will require mastering materials science and performance issues, particularly those associated with materials degradation due to bombardment by the energetic (14.1 MeV) deuterium-tritium (D-T) fusion neutrons. This performance degradation provides the basis for and is one of the largest inherent limiting factors for the economic, safety, and environmental attractiveness of fusion energy. The FPNS device will be designed and built to provide a high-throughput (greater than 5 dpa/year in 50 cm^3) fusion irradiation capability consistent with community specified requirements and will provide critical scientific and engineering data for both Fusion Pilot Plant (FPP) and commercial fusion energy systems. This facility could be located at a national laboratory (or lab-class facility at a R1 university) or hosted by a private company as a Public/Private partnership. FPNS is pre-CD-0.

D-IIID Upgrade (eXcite)

Total Project Cost (TPC) range of $75M-$300M

Addressing the core/exhaust integration challenge requires a new tokamak facility, the EXhaust and Confinement Integration Tokamak Experiment (eXcite). High-magnetic field approaches to a tokamak-based FPP raise specific scientific and engineering challenges. High-divertor-power exhaust solutions need to be integrated with sustainment of high-power-density plasma cores, which are needed for generation of significant fusion power. Both the NASEM Burning Plasma Report and the Community Planning Process (CPP) report identify the need to address these challenges in an integrated fashion, rather than at separate facilities. This requirement motivates the need for construction of a new domestic tokamak, previously referred to as NTUF (New Tokamak User Facility) in the CPP report. This project will be located at General Atomics to take advantage of existing D-IIID infrastructure. eXcite is pre CD-0.

Blanket Component Test Facility (BCTF)

Total Project Cost (TPC) range of $130M-$520M

Blanket research and the associated BCTF will provide the scientific understanding and basis to qualify fusion power system blankets for an FPP. The CPP report outlines an R&D program on blanket materials and transport phenomena that culminates in the design and fabrication of blanket-section prototypes, which undergo staged testing in a BCTF. The CPP report describes a BCTF that integrates all non-nuclear features of a fusion blanket and its ancillary systems (prototypic, at-scale complex structures and coolants) under prototypic conditions of temperature, pressure, magnetic field, and mechanical stress, with surrogate surface and volumetric heating and injected hydrogen or deuterium in place of tritium. Concepts successfully vetted in the BCTF, and fission and/or fusion irradiations, could potentially proceed to full nuclear testing and tritium production. This project could be hosted at a university, national laboratory or a private company as part of a Public/Private partnership. BCTF is pre-CD-0.

High Heat Flux Test Facility (HHF)

Total Project Cost (TPC) range of $90M-$360M

Testing capabilities to explore properties of materials and plasma-facing components, both solid and liquid, under high heat fluxes addresses a key gap toward FPP material definitions. Experimental capabilities to conduct fundamental testing on coupon levels (centimeter scale) are a necessary testbed for model validation of material properties. The coupon level testing is a prerequisite for component-level testing (tens of centimeters to meters scale) to qualify components for an FPP. Accordingly, testing facilities for both levels of high-heat-flux materials research are required. This project could be hosted at a university, national laboratory or a private company as part of a Public/Private partnership. HHTF is pre- CD-0.

Midscale Stellarator

Total Project Cost (TPC) range of $180M-$720M

A proof-of-concept stellarator experimental facility is needed to demonstrate improved steady-state plasma confinement in combination with a novel non-resonant divertor. Development of this stellarator research line could provide risk mitigation for the mainline tokamak approach and could lead to a commercially more attractive fusion system. The mid-scale stellarator facility would be a discoveryoriented research facility that could stimulate a great deal of innovation. This facility could be located at a university or national lab. This project is pre-CD-0.

NSTX-U Liquid Metal/Core Edge Facility (LMCE)
Total Project Cost (TPC) range of $75M-$300M

Liquid-metal plasma-facing components have the potential to ameliorate some of the extreme challenges of the plasma-solid interface and may reveal new plasma operating regimes. Liquid metal plasma-facing components potentially expand the reactor-wall power limits and alleviate lifetime constraints due to material erosion. Low-recycling, liquid lithium walls may open pathways to high plasma confinement and compact FPP designs. Development of liquid metal plasma-facing-component concepts in non-plasma test stands and existing magnetic confinement facilities should be targeted and should build on PFC concepts developed in the existing domestic program. Core-edge innovation coupled to LM PFC concepts in an integrated high aspect ratio spherical tokamak configuration is a unique opportunity for U.S. to take leadership and as a test hub for industry stakeholders. This facility would be located at Princeton Plasma Physics Laboratory (PPPL) to take advantage of existing infrastructure. LMCE is pre-CD-0.

Fuel Cycle Test Facility (FCTF)
Total Project Cost (TPC) range of $125M-$500M

Creating/developing a continuously operational deuterium-tritium (D-T) fuel cycle that can efficiently breed, extract, process, and inject tritium back into the plasma, with an eye toward minimizing inventory of this limited resource, is critical for fusion to achieve its environmental/safety potential as a future energy resource. The FCTF will need to have the testing/experimental capabilities to test all aspects of the fuel cycle systems/technology including separating all the different types of impurities from the hydrogen isotopes that will come from the plasma exhaust and the various blanket concepts, isotopically separating the hydrogen isotopes, and then providing the D-T fuel back into the fusion device to keep it operating. The FCTF will also be a test bed to enhance the scientific foundation of tritium exposure to all the various materials/components that will encounter it. This facility is best located at a National Laboratory due to tritium handling considerations. FCTF is pre-CD-0.

Fusion Integration Research and Science Test Facility (FIRST)
Total Project Cost (TPC) range of $800M-$3.2B

The FIRST project is envisioned as an integrated test facility which encompasses the key research capabilities provided by many single purpose test facilities. Economies of scale can be leveraged by operating a singled facility to address the materials science and performance issues, particularly those associated with materials degradation due to bombardment by the energetic (14.1 MeV) deuterium-tritium (D-T) fusion neutrons; the nuclear features of a fusion blanket and its ancillary systems (prototypic, at-scale complex structures and coolants) under prototypic conditions of temperature, pressure, magnetic field, and mechanical stress, with surrogate surface and volumetric heating and injected hydrogen, deuterium as well as tritium. FIRST will also allow for the testing of all aspects of the fuel cycle systems/technology including separating all the different types of impurities from the hydrogen isotopes that will come from the plasma exhaust and the various blanket concepts, isotopically separating the hydrogen isotopes, and then providing the D-T fuel back into the fusion device to keep it operating. In addition, the facility would generate neutrons from a plasma core that could be a torus-based fusion configuration (e.g. tokamak or spherical tokamak) or non-torus (mirror, FRC, inertial fusion-based). With a nominal plasma core, additional gaps on plasma sustainment and core-edge could be used in an integrated design for accelerating development of fusion energy. This facility could be hosted at a National Laboratory or at a private site as part of a Public/Private partnership. FIRST is pre-CD-0.

Appendix B: Sub-Committee Members

Prof. Brian Wirth, U. of Tennessee - Knoxville (Chair)

Prof. Carlos Paz-Soldan, Columbia University (Vice-Chair)

Dr. Felicie Albert, Lawrence Livermore National Laboratory

Mr. David Babineau, Savannah River National Laboratory

Dr. Kate Bell, Sandia National Laboratories

Dr. Cami Collins, Oak Ridge National Laboratory

Prof. Evdokiya Kostadinova, Auburn University

Dr. Rajesh Maingi, Princeton Plasma Physics Laboratory

Prof. Jaime Marian, U. of California - Los Angeles

Dr. Thomas Sunn Pedersen, Type One Energy

Dr. Erica Salazar, Commonwealth Fusion Systems

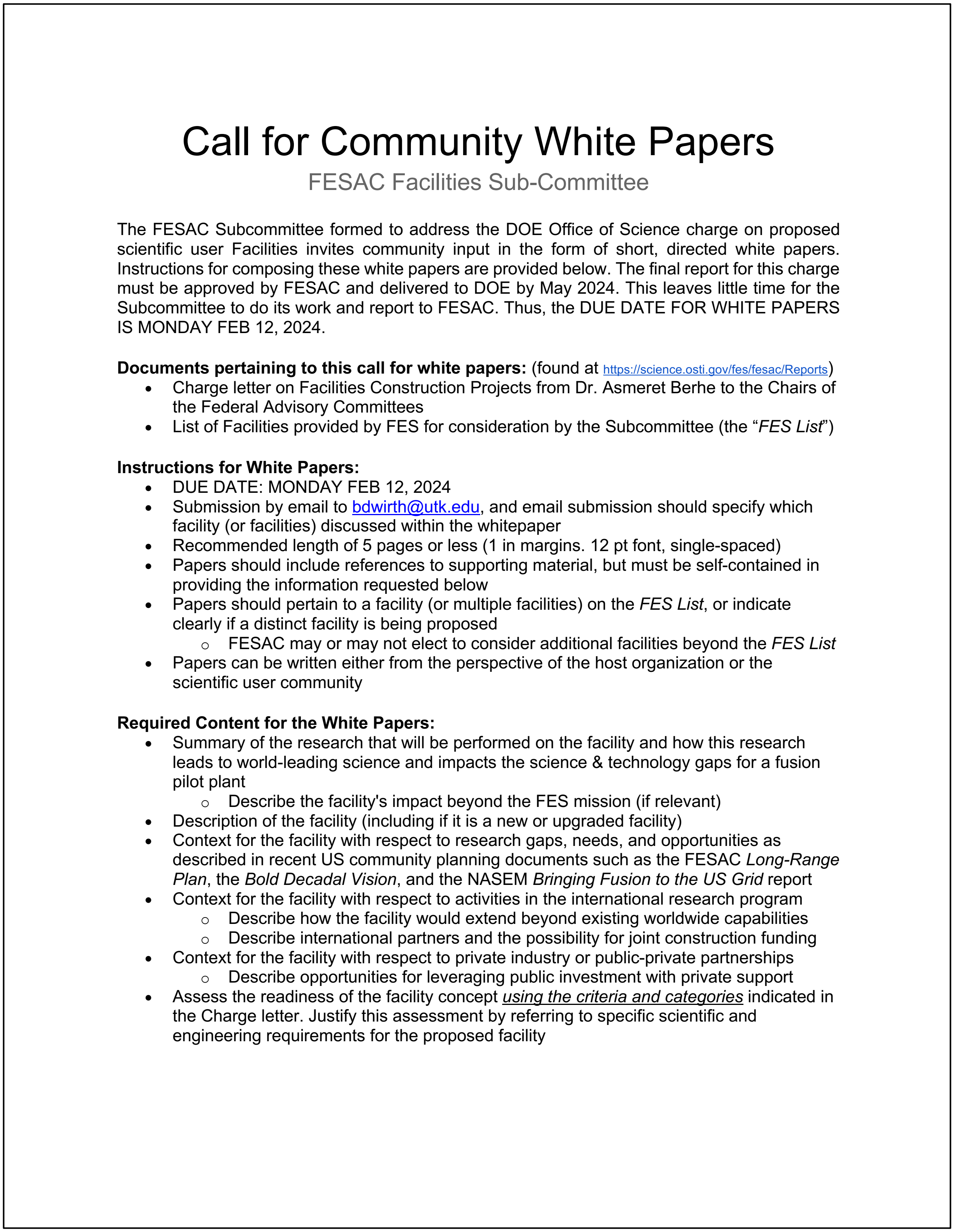
Dr. Chase Taylor, Idaho National Laboratory

Dr. Kathreen Thome, General Atomics

Prof. Troy Carter, U. of California - Los Angeles (ex-officio)

Prof. Anne White, Massachusetts Institute of Technology (ex-officio)

Appendix C: Call for White Papers & List of White Papers



Call for Community White Papers

FESAC Facilities Sub-Committee

The FESAC Subcommittee formed to address the DOE Office of Science charge on proposed scientific user Facilities invites community input in the form of short, directed white papers. Instructions for composing these white papers are provided below. The final report for this charge must be approved by FESAC and delivered to DOE by May 2024. This leaves little time for the Subcommittee to do its work and report to FESAC. Thus, the DUE DATE FOR WHITE PAPERS IS MONDAY FEB 12, 2024.

Documents pertaining to this call for white papers: (found at https://science.osti.gov/fes/fesac/Reports)
- Charge letter on Facilities Construction Projects from Dr. Asmeret Berhe to the Chairs of the Federal Advisory Committees
- List of Facilities provided by FES for consideration by the Subcommittee (the "*FES List*")

Instructions for White Papers:
- DUE DATE: MONDAY FEB 12, 2024
- Submission by email to bdwirth@utk.edu, and email submission should specify which facility (or facilities) discussed within the whitepaper
- Recommended length of 5 pages or less (1 in margins. 12 pt font, single-spaced)
- Papers should include references to supporting material, but must be self-contained in providing the information requested below
- Papers should pertain to a facility (or multiple facilities) on the *FES List*, or indicate clearly if a distinct facility is being proposed
    - FESAC may or may not elect to consider additional facilities beyond the *FES List*
- Papers can be written either from the perspective of the host organization or the scientific user community

Required Content for the White Papers:
- Summary of the research that will be performed on the facility and how this research leads to world-leading science and impacts the science & technology gaps for a fusion pilot plant
    - Describe the facility's impact beyond the FES mission (if relevant)
- Description of the facility (including if it is a new or upgraded facility)
- Context for the facility with respect to research gaps, needs, and opportunities as described in recent US community planning documents such as the FESAC *Long-Range Plan*, the *Bold Decadal Vision*, and the NASEM *Bringing Fusion to the US Grid* report
- Context for the facility with respect to activities in the international research program
    - Describe how the facility would extend beyond existing worldwide capabilities
    - Describe international partners and the possibility for joint construction funding
- Context for the facility with respect to private industry or public-private partnerships
    - Describe opportunities for leveraging public investment with private support
- Assess the readiness of the facility concept *using the criteria and categories* indicated in the Charge letter. Justify this assessment by referring to specific scientific and engineering requirements for the proposed facility

Communicating Author(s)	Institution	Title	Facility(ies)
C. Swanson et al.,	Thea Energy	The Case for a public, flexible mid-scale stellarator facility	Stellarator
B. Garcia-Diaz et al.,	SRNL	Tritium and fuel cycle research facility needs (including FCTF and co-located facilities)	FCTF
L. Peddicord et al.,	Texas A&M	Proposal for the DOE inertial fusion user facility at Texas A&M University	New IFE
K.A. McCarthy, et al.,	Various	The crucial role of ITER for advancing U.S. Fusion Energy	ITER
W. Guttenfelder, et al.,	Type One Energy	The type one energy risk retirement platform (RRP) as a midscale stellarator research facility	Stellarator
L. Baylor, et al.,	ORNL	A fuel cycle test facility for fusion energy development	FCTF
C. Deeney et al.,	U Rochester LLE	Additional Omega Facility capacity to support laser fusion energy	New IFE
D.J. Sprouster, D. Winklehner, D. Whyte, S. Zinkle, Z. Hartwig, and L.L. Snead	Various	Enabling a compact-fusion prototypic neutron source with High-Current Compact Cyclotrons	FPNS
R.F. Radel, L.M. Reusch, L.J. Jacobson	SHINE Technologies	Intermediate Flux DT neutron tritium breeding facility	New, BCTF & FCTF
P. Ferguson, et al.,	Various	Accelerating the delivery of fusion energy with a fusion prototypic neutron source (FPNS)	FPNS & FIRST
B. Grierson et al.,	General Atomics	A blanket component test facility (BCTF) at General Atomics as a centerpiece for U.S. leadership in fusion	BCTF
B. Grierson et al.,	General Atomics	A fusion integrated research and science test facility to bring advanced technologies online	FIRST
P. Humrickhouse, E. Unterberg, C.S. Wiggins, and T.K. Gray	ORNL	A modular, component high heat flux user facility (C-HUF)	HHF
L. Snead et al.,	Various	The necessity for a domestic high heat flux facility and suggested technology	HHF
H. Wilson et al.,	Various	FIRST to commercialize fusion energy	FIRST

P. Humrickhouse, L. Baylor, M. Gehrig, and H. Wilson	ORNL	Blanket component test facility	BCTF
M. Shafer, et al.,	ORNL	EXCITE: A direct impact to de-risk the tokamak	EXCITE
J. Menard et al.,	Various	NSTX-U LMCE	NSTX-U LMCE
J. Zuegel, J. McCarick, V. Tang	Various	Advancing Laser Technologies to Reduce Risks for Inertial Fusion Energy	New IFE
G. Wallace et al.,	Various	Radio Frequency Technology Development Center (RF-TECH)	New
A. Fry et al.,	Various	Matter in Extreme Conditions Petawatt Upgrade (MEC-U)	MEC-U
C.M. Jacobson et al.,	Realta	The magnetic mirror as a fusion prototypic neutron source and fusion integration research and test facility	FPNS & FIRST
F.I. Parra et al.,	Various	Flexible stellarator physics facility	Stellarator
N. Pablant et al.,	Various	The compelling need for a mid-scale stellarator facility	Stellarator
R.J. Buttery et al.,	Various	DIII-D upgrade (Excite) to meet the core-edge integration challenge for an FPP	DIII-D Upgrade
D.R. Hatch, M. Kotschenreuther, S. Mahajan and F. Waelbroeck	UT Austin	Capabilities needed in next step facilities to bridge the ITEP gap	EXCITE, NSTX-U LMCE, HHF
P. Calderoni, M. Shimada, T. Fuerst, and M. Eklund	INL	The need for a nuclear component test facility	New
J. Edwards, F. Graziani et al.,	Various	A new facility for public-private partnerships to drive innovation in inertial fusion energy	New IFE
Z. Hartwig et al.,	Various	A world-leading U.S. consortium of superconducting magnet test facilities to advance fusion energy	New
M.L. Reinke, R. Mumgaard and M. Segal	CFS	Revisiting the role of EXCITE in the essential mission to close the ITEP gap	EXCITE

M.L. Reinke, T. Eich, R. Mumgaard and M. Segal	CFS	SPARC for the EXCITE mission	EXCITE
D. Young and M. Segal	CFS	A public private partnership FLiBe blanket component test facility (F-BCTF)	BCTF
A. Creely, M. Segal, R. Mumgaard and R. Needham	CFS	Achieving the FIRST mission with ARC	FIRST
A. Creely, B. Mumgaard & M. Greenwald	CFS	Burning Plasma Physics in SPARC	ITER
S. Dorfman et al.	Various	Next generation solar wind facility for discovery plasma science	New
V. Tang	LLNL	Laser driven fusion prototypic neutron sources (LD-FPNS) for material irradiation studies	FPNS
J. Galbraith, V. Tang, M. Dunne and B. Garcia-Diaz	Various	LD-FIRST (Laser driven fusion integration research & science test facility)	FIRST
M. Austin, A. Marinoni, G.R. McKee, and F. Scotti	Various	A negative triangularity tokamak to solve the core-edge integration fusion challenge	EXCITE
Y. Kato et al,	Various	Science Drivers for Fusion Prototypic Neutron Source (FPNS)	FPNS
N. Gorelenkov et al	PPPL	Energetic Particles - Microturbulence Interaction Thrust	ITER

Appendix D: List of Webinars

Date	Facility	Speaker(s)	Title(s)
2/15/24	MEC-U	A. Fry (SLAC)	Status of Material in Extreme Conditions (MEC) Upgrade plans
2/22/24	ITER	K. McCarthy (ORNL) C. Greenfield (ORNL)	Status of ITER project
2/29/24	NSTX-U LMCE	J. Menard (PPPL) R. Goldston (PPPL)	Status of plans for liquid metal/core edge (LMCE) upgrade to NSTX-U
3/5/24	DIII-D Upgrade	R. Buttery (GA)	Status of plans for DIII-D eXcite upgrade
3/7/24	FPNS	P. Ferguson (ORNL) K. Field (U Mich)	Status of Fusion Prototypic Neutron Source plans
3/12/24	BCTF	P. Humrickhouse (ORNL), D. Young (CFS), L. Baylor (ORNL), B. Grierson (GA), R. Radel (Shine), P. Calderoni (INL)	Community overview of BCTF (P. Humrickhouse), then short presentations by CFS, ORNL, GA, Shine and INL
3/14/24	HHF	L. Snead (Stony Brook), D. Sprouster (Stony Brook), T. Gray (ORNL) M. Gorley (UKAEA)	Community overview of HHF (L. Snead), then short presentations by Stony Brook, ORNL, and UKAEA (CHIMERA facility)
3/21/24	EXCITE Options	D. Hatch (UT Austin) M. Reinke (CFS), M. Shafer (ORNL), M. Austin (UT-Austin)	Short presentations pertaining to different EXCITE options
3/26/24	Mid-Scale Stellarator	N. Pablant (PPPL), B. Geiger (Wisc), F. Parra (PPPL), C. Swanson (Thea), W. Guttenfelder (Type One)	Community overview of Mid-Scale Stellarator (N. Pablant), then short presentations by NSCC, PPPL, Thea, Type One Energy
3/28/24	FIRST	A. Creely (CFS), C. Jacobson (Realta), H. Wilson (ORNL), B. Grierson (GA), M. Dunne (SLAC)	Short presentations by CFS, Realta, ORNL, GA, and SLAC/LLNL
4/2/24	FCTF	B. Garcia-Diaz (SRNL) L. Baylor (ORNL), S. Wheeler (UKAEA)	Community overview of FCTF (B. Garcia-Diaz), followed by short presentations by ORNL, SRNL and UKAEA (H3AT facility)
4/4/24	New IFE	Hafner (Fraunhofer), Peddicord (Texas A&M), Deeney (Rochester), Edwards (LLNL)	Community overview of IFE basic research needs (C. Hafner), then short presentations by Texas A&M, Rochester, LLNL

Appendix E: Criteria to Guide Discussions

The following criteria were used to guide the discussions of each facility as it related to the two parts of the second charge question.

Charge 2a – "Potential to Contribute to World-Leading Science in the Next Decade"

1. Is the proposed facility (facility upgrade for DIII-D and NSTX-U) aligned with the long-range plan (LRP) and bold decadal vision (BDV), as reflected in the recent NASEM report "Bringing Fusion to the U.S. Grid"?

2. Does the facility, or facility upgrade, offer the potential for world-leading foundational fusion science, or does it contribute to one or more enabling science/technology gaps in support of developing a competitive fusion industry (contribution to one or more gaps could be assessed in terms of advanced technical readiness levels)?

3. Will the proposed facility (or upgrade) contribute to uniqueness and/or US Leadership within the International fusion landscape?

4. Will the proposed facility (or upgrade) contribute to advancing the US private fusion sector?

5. Will address the needs of a broad community of users or apply to multiple concepts?

Charge 2b – "Readiness for Construction"

1. How well established is the proposed facility (or proposed upgrades) and proposed site location?
    - how many proposed options are available? (diversity of possible bids – this drives competition to reduce cost, schedule, etc.)

2. At what level are technical risks, and required enabling R&D, and cost range be readily documented for the proposed facility (or proposed upgrades)?

3. Can partnerships, either international or with the private sector, accelerate readiness for construction?

4. Does the workforce exist to enable construction?

Appendix F: List of Acronyms

BCTF	Blanket Component Test Facility
BDV	Bold Decadal Vision [3]
CPP	Community Planning Process
DOE	Department of Energy
EPRI	Electric Power Research Institute
FCTF	Fuel Cycle Test Facility
FES	Fusion Energy Sciences
FESAC	Fusion Energy Sciences Advisory Committee
FCP	Facilities Construction Projects
FIRST	Fusion Integration Research and Science Test Facility
FNSF	Fusion Nuclear Science Facility
FPNS	Fusion Prototypic Neutron Source
FPP	Fusion Pilot Plant
FRC	Field-Reversed Configuration
HED	High Energy Density
HHF	High Heat Flux Test Facility
IFE	Inertial Fusion Energy
MEC-U	Matter in Extreme Conditions Petawatt Laser Upgrade
MFE	Magnetic Fusion Energy
NASEM	National Academy of Science, Engineering, & Medicine
NSTX-U	National Spherical Torus Experiment Upgrade
NNSA	National Nuclear Security Administration
LM	Liquid Metal
LMCE	Liquid Metal Core Edge Facility
LRP	Long-Range Plan [9]
TBM	Test Blanket Module
TRL	Technology Readiness Level
PFC	Plasma-Facing Component
PFM	Plasma-Facing Materials
PPP	Public-Private Partnership
UKAEA	United Kingdom Atomic Energy Agency
VNS	Volumetric Neutron Source

Appendix G: References

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