FSP Plan Executive Summary

The Fusion Simulation Program (FSP) addresses important scientific questions with urgent practical impact on the development of magnetically-confined plasmas as a clean and sustainable supply of energy. Building the scientific foundations needed to develop fusion energy, requires the timely development of an integrated high-physics-fidelity predictive simulation capability for fusion plasmas. Projections for plasma performance in ITER -- a multi-billion dollar international experimental device being built in Cadarache, France and involving the partnership of seven governments representing over half of the world's population -- have been based on simplified computational models developed from past knowledge. However, reliable operation will demand careful planning based on more accurate modeling of the integrated physics of the burning plasmas in ITER as our knowledge continues to significantly improve. Compared to existing experiments, ITER represents a significant extrapolation in the duration/pulse length of each shot/discharge and in the energy exhausted to the periphery of the system. Since each shot is expected to cost over $1M, a strong effort is needed to optimize operation, data collection, and data analysis. Accordingly, the FSP will initially focus on producing: (i) validated comprehensive models of the plasma boundary and the interactions of the plasma with the surrounding wall; (ii) whole device models for the analysis, planning, and optimization of discharge scenarios capable of avoiding disruptions -- the large-scale macroscopic events leading to rapid termination of plasma discharges. Since the consequences of disruptions will be severe for ITER and reactor-scale devices, reliable prediction of high-performance plasma evolution and the margin for avoiding disruptions will be an indispensable part of discharge planning. Overall, the nonlinear interaction of the plasma with control actuators is too complex to investigate effectively by empirical methods alone. Thus, modeling to guide exploration has proven to be an essential and successful strategy that will be enhanced to an unprecedented level of realism by the FSP.

The problems targeted by the FSP were chosen by consideration of key priorities articulated by the ITER organization (IO), the Fusion Energy Science (FES) community Research Needs Workshop (ReNeW) document, the U.S. Fusion Facilities Coordinating Committee (FFCC), other international facilities (e.g., in Asia with long pulse experimental capabilities not available in US facilities), and with strong community engagement via numerous major workshops and individual site visits to laboratories, universities, and industries. The FSP planning began by identifying and then following a set of prioritization criteria that includes: (i) a clear need for multi-scale, multi-physics integration; (ii) importance and urgency; (iii) readiness and tractability; and (iv) opportunities for new lines of research that produce new insights/potential breakthroughs inaccessible by other means.

The plan assumes that, as the FSP progresses and demonstrates success, the program will evolve and grow, enabling additional integration opportunities to be addressed. These could include (i) mitigating disruptions if they cannot be completely avoided; (ii) profile information in the plasma core region needed to determine operational limits; and (iii) interactions between energetic particles and electromagnetic waves that influence the efficacy of auxiliary heating of the plasma and the fast-particle confinement of fusion products. In addressing these important problems, the FSP will rely on collaborations with DoE's Scientific Discovery through Advanced Computing (SciDAC) program. Over the course of the next five years, the ongoing FES SciDAC projects – together with the FES base Theory Program -- will continue to carry out the basic research needed to provide the foundations for these future Integrated Science Application (ISA) areas.

The FSP scope will require sufficiently large scale to address these complex problems and to enable much greater scientific productivity through the delivery of robust community codes. It will include a coordinated national staff dedicated for software infrastructure, developer support, production computing, and user support - instead of the current less efficient practice of diffuse development and support of individual applications. The FSP alliance with the office of Advanced Scientific Computing Research (ASCR) will help ensure that modern applied mathematics and computer science technologies will be deployed with rapid sharing of new tools and approaches between application. The FSP will feature: (i) efficient integration of best physics components with common interfaces and data structures guided by an appropriate set of standards; (ii) production of FSP-standardized, well-documented tool sets for data preparation, code input validation, data analysis, and visualization FSP standards; (iii) unprecedented world-class standards for physics fidelity through the application of modern validation, verification and uncertainty quantification that enable more rigor and efficiency via strong coordination with experimental national and international facilities; and (iv) training of a new generation of "analysts" with a breadth of multi-disciplinary skills, which will involve strong university participation in the FSP.

The overarching science goals of the FSP will entail development of a suite of advanced software codes designed to utilize leadership class computers effectively for carrying out multi-scale multi-physics simulations that deliver a realistic integrated fusion simulation capability with unprecedented fidelity in physics models, solution accuracy, and geometric representation. These codes will represent a realistic measure of the theoretical and experimental understanding of magnetically-confined thermonuclear plasmas and provide the frameworks and infrastructure for integrated physics simulation of fusion plasmas as understanding continues to advance over the next several decades. In accomplishing this objective, the FSP will require a wide spectrum of computing resources and must leverage DoE's leadership class facilities in the petascale range and beyond. The FSP will also leverage scientific programs in FES, ASCR, and the SciDAC Program, which already features effective interdisciplinary collaborations between computer science, applied mathematics, and many domain applications areas, including FES. Sustained petascale and even exascale (10^{18} floating point operations per second) platforms (likely to appear circa 2020) will be needed to meet the future challenges associated with the design of the demonstration reactor (DEMO).

The FSP goal also demands close collaborations to validate the new codes against data and dedicated experiments from national and international magnetic fusion facilities. In this regard, it is worth noting that the U.S. facilities collectively field the best set of diagnostic measurements in the world and have committed themselves to a vigorous collaboration with the FSP. A successful FSP will enhance the return on investments in fusion experiments in general and help ensure the success of ITER by enabling the harvesting of scientific insights from a sustained burning plasma experiment. This in turn can enable discovery of new modes of operation with possible extensions of performance enhancements and improvements needed for DEMO.

Overall, the FSP will embody our state of knowledge in a suite of advanced codes under a unified framework and made widely available to the FES community. Unique benefits for Fusion Energy Science include:

- Addressing multi-physics and multi-scale problems that are now treated in isolation, leading to scientific discovery of new phenomena that emerge only with integration;
- Carrying out a rigorous and systematic validation program in collaboration with experiments to put models on the firmest and most realistic possible foundation;
- Identifying a set of Science Drivers as forefront scientific problems in FES and developing a "living roadmap" to address them as Integrated Science Applications that will be aided by computing at the extreme scale in collaboration with ASCR;
- Developing predictive models that improve our capabilities for reliable scenario modeling, especially for ITER, and for the design of a future demonstration reactor (DEMO);
- Incorporating powerful high performance computing (HPC) capabilities to help accelerate scientific understanding and modern software engineering approaches to ensure the reliability, robustness, and ease-of-use by the fusion community of the new tools that are developed;
- Achieving economies of scale created through the development of a community infrastructure that will enhance collaboration and reduce duplication of effort; and
- Leveraging ongoing activities (theory, experiment, modeling in FES and applied math and computer science in ASCR) to develop world-leading simulation capabilities with unprecedented physics fidelity.