Planning for U.S. Fusion Community Participation in the ITER Program

Prepared by the

U.S. Burning Plasma Organization

Energy Policy Act Task Group

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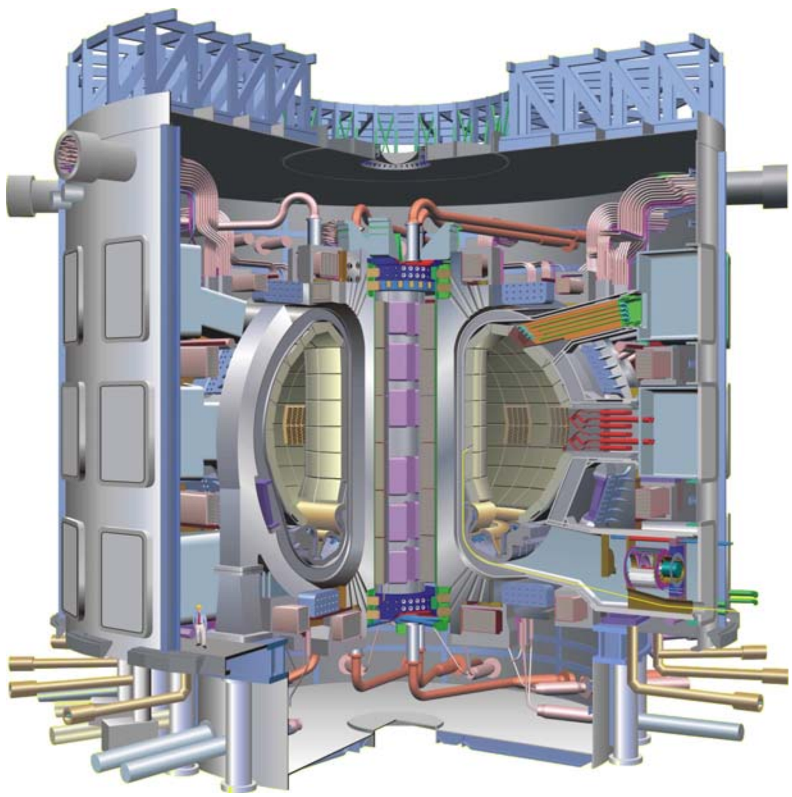

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Executive Summary

A central step in the mission of the U.S. Fusion Energy Sciences program is the creation and study of a fusion-powered "star on earth", where the same energy source that drives the sun and other stars is reproduced and controlled for sustained periods in the laboratory. This “star” is formed by an ionized gas, or plasma, heated to fusion temperatures in a magnetic confinement device known as a tokamak, which is the most advanced magnetic fusion concept. The ITER tokamak is designed to be the premier scientific tool for exploring and testing expectations for plasma behavior in the fusion burning plasma regime, wherein the fusion process itself provides the dominant heat source to sustain the plasma temperature. It will provide the scientific basis and control tools needed to move toward the fusion energy goal.

The ITER project confronts the grand challenge of creating and understanding a burning plasma for the first time. The distinguishing characteristic of a burning plasma is the tight coupling between the fusion heating, the resulting energetic particles, and the confinement and stability properties of the plasma. Achieving this strongly coupled burning state requires resolving complex physics issues and integrating challenging technologies. A clear and comprehensive scientific understanding of the burning plasma state is needed to confidently extrapolate plasma behavior and related technology beyond ITER to a fusion power plant. Developing this predictive understanding is the overarching goal of the U.S. Fusion Energy Sciences program.

The burning plasma research program in the U.S. is being organized to maximize the scientific benefits of U.S. participation in the international ITER experiment. It is expected that much of the research pursued on ITER will be based on the scientific merit of proposed activities, and it will be necessary to maintain strong fusion research capabilities in the U.S. to successfully contribute to the success of ITER and optimize the benefits to the U.S. from ITER participation. To that end, a U.S. Burning Plasma Organization has been formed to help focus U.S. fusion research activities needed to support burning plasma research. In addition, U.S. scientists participate in the International Tokamak Physics Activity to coordinate these activities with international partners. U.S. scientists also collaborate directly with international colleagues through several multilateral International Energy Agency implementing agreements and through U.S. bilateral agreements with the European Union and other ITER partners.

The three elements of the Plan for the participation of U.S. scientists in ITER are described in this report. This Plan was prepared by the USBPO at the request of Office of Fusion Energy Sciences in response to the requirement in the Energy Policy Act of 2005.

Element 1: The U.S. research agenda for ITER

The U.S. research agenda for ITER addresses four fundamental questions relevant to understanding fusion plasmas and the surrounding environment:

- How does the large size of the plasma required for a fusion power plant affect its confinement, stability, and energy dissipation properties?
- Can a self-heated fusion plasma be created, controlled, and sustained?
- Can the tokamak confinement concept be extended to the continuous, self-sustaining regime required for future power plants?
- What materials and components are suitable for the plasma containment vessel and its surrounding structures in a fusion power plant?

The U.S. fusion science program is organized around six major scientific and technological campaigns that cover the breadth of issues arising from confronting these questions. An initial plan for U.S. research in ITER has been developed around these campaigns. Each science campaign contains two or more specific goals for ITER to assure successful operation of the experiment or develop an understanding of the fusion plasma environment. Achieving these goals collectively develops answers to the four central questions posed above.

Pursuing these long-term scientific goals in ITER requires well-defined, long-term R&D activities in each of the priority science areas. These efforts span from the present design support stage, to experimental demonstration and investigation of burning plasmas, and through the high-power, long-pulse technology test stage of ITER operation. Planning backwards from each long-term goal for ITER operation identifies the required preparation activities. An active domestic research program in both experiment and theory will be crucial before and during operation of ITER, both to support ITER's objectives and take full scientific advantage of the knowledge gained from ITER.

***Element 2*: Methods to evaluate whether ITER is promoting progress toward making fusion a reliable and affordable source of power**

Progress on critical scientific and technology issues needed to design future fusion energy power plants will be evaluated with metrics based on increased scientific understanding and performance in the burning plasma regime. To evaluate this progress, the research plan toward the fusion goal should be periodically assessed and modified by internal and external reviews.

The focus of the U.S. Fusion Energy Sciences program is the development of a predictive understanding of the fusion plasma system to support moving beyond ITER. A metric for progress in scientific understanding is whether the specific goals that collectively define the research agenda discussed above are achieved in the expected time frames. The level of agreement among theory, simulation, and experiment measures progress toward these goals. Another measure of scientific progress is the ability to use that knowledge to extend plasma performance toward that needed for fusion power. The ultimate measure of progress in scientific understanding, however, is obtained through periodic peer review of the research activities performed.

Plasma performance metrics are derived from specific technical goals on ITER and fusion power plant studies that have identified the major scientific and technological goals for an attractive fusion power plant. They include issues such as fusion power, fusion power gain, plasma pressure, power density, power dissipation, and neutron wall loading. Comparison of these parameters achieved in ITER to those required for a conceptual demonstration power plant provides an array of objective measures of the progress toward fusion power.

Element 3: Description of how work at ITER will relate to other elements of U.S. fusion research program

The research agenda for ITER includes experiments on tokamaks and related experiments, theory, and engineering science in the U.S. program. This direct support of ITER is an integral part of the U.S. fusion research program. Complementing this ITER support, the program also includes a broad range of research activities to ensure that the U.S. will have an adequate knowledge base for developing an attractive fusion power source.

While ITER will move magnetic fusion significantly closer to the fusion energy goal, a comparison between ITER and prototypical power plant parameters indicates the need for further improvements in plasma pressure, energy confinement, power requirements, simplicity and reliability. The U.S. is addressing these needs with a science-based program that aims to broaden the understanding of fusion science and technology and thereby establish the knowledge base to determine the steps beyond ITER.

The main components of this program are large experiments in four magnetic configurations (the advanced tokamak, spherical torus, stellarator, and reversed field pinch), enabling technology, theory and computation, and a portfolio of small-scale experiments examining emerging concepts in magnetic confinement science. It also includes stewardship of fundamental plasma physics, the science of this fourth state of matter. Through participation in ITER, the U.S. will obtain the burning plasma knowledge that is needed, in combination with the broadened knowledge base from the U.S. program, to predict a path to practical fusion energy.

I Introduction and Overview

I.A Preparing for Participation in ITER

I.A.1 Introduction

⇒ Creating and controlling the first sustained “star on earth” in ITER for future energy production is a grand scientific, technological, and organizational challenge.

The mission of the U.S. Fusion Energy Sciences program is: “To advance plasma science, fusion science, and fusion technology – the knowledge base needed for an economically and environmentally attractive fusion energy source.” A central step forward in pursuit of that mission is the creation of a fusion-powered "star on earth", where the same energy source that drives the sun and other stars is reproduced and controlled for sustained periods in the laboratory. Its importance to the development of the science necessary for fusion energy was emphasized by a recent National Academies study, which stated, "…A burning plasma experiment is a key scientific milestone on the road to the development of fusion power…." Recognizing this importance, the U.S. joined the international ITER Organization to provide the U.S. science community the opportunity to study this unique environment and thereby develop the scientific and technological knowledge base needed to move toward practical fusion power.

The extremely hot ionized gas that comprises the fuel of a fusion energy system, known as a plasma, is said to be burning when the fusion reactions themselves provide as much or more power to heat the plasma than any external heating source. Achieving and studying the properties of a burning plasma defines the very frontier of the science of high-temperature plasma physics and its interactions with its containment vessel and surrounding structures.

ITER is designed to be the premier scientific tool for exploring and testing expectations of plasma behavior in the burning plasma regime. It is a magnetic confinement device, known as a tokamak, which is the most advanced magnetic confinement configuration. It will provide the scientific basis for developing the predictive capability and testing control tools needed to move toward the fusion energy goal. This scientific understanding of the burning plasma state, plus concurrent fusion technology and concept optimization developments, will produce the knowledge base and tools needed to design a next-step demonstration energy-producing device.

Throughout this discussion, it is recognized that the integrated international ITER Organization, of which the U.S. Fusion Energy Sciences program will be a member, will coordinate most of the research on ITER. Hence, the details of the U.S. research agenda for ITER will evolve accordingly to reflect planning activities of the international community. However, the main U.S. goals are robust and consistent with high-level ITER objectives for which there is broad agreement among the partners. This discussion summarizes the present plan for U.S. participation in ITER and the related burning plasma research program, in response to the three elements in Section 972 (c)(4)(A) (i-iii) in the Energy Policy Act of 2005. Detailed responses to each of the charges are given in Chapters II-IV.

I.A.2 Science and Technology Questions Addressed by Research on ITER

The study of the man-made "star on earth" in ITER allows the fusion research community to address four fundamental questions that arise in the pursuit of the knowledge base for fusion energy. Developing the understanding to answer these questions represents the science and technological challenge of understanding a burning plasma.

- **LARGE-CONFINEMENT-SCALE PHYSICS:**
  How does the large size of the plasma required for a fusion power plant affect its confinement, stability, and energy dissipation properties?
  The number of particle orbits that can fit inside the hot plasma volume is the measure of the effective size of a magnetic fusion facility. Theory and experiment suggest that this effective size can have a strong influence on plasma stability, energy transport and the energy dissipation properties of the plasma. A large effective size is needed for sufficient confinement and reasonable heat loads in a power plant. The effective size of the plasma in a projected fusion power plant will be a factor of about two times that realized in any experiments to date. ITER will provide critically needed data to test the understanding of these unresolved issues at the large scale expected for a fusion power plant.

- **THE BURNING PLASMA STATE:**
  Can a self-heated fusion plasma be created, controlled, and sustained?
  The grand scientific and technological challenge of ITER is that of creating a strongly coupled burning plasma for the first time. The fundamentally new element in a burning plasma is that the fusion process itself will provide the dominant source of heating in the plasma. This internal heating will influence the plasma stability and its capacity to maintain sufficient insulation from the surrounding chamber to allow sustainment of the fusion process. The energetic particles produced by the fusion reactions may also interact with the plasma and further influence its ability to maintain stability and/or sustain its self-heating process. The strong coupling among this internal heating, the energetic particles, and the confinement and stability properties increasingly determines the ability of the plasma to organize itself in a sustained burning plasma state. This strong internal coupling of the plasma properties is related to the emergent field of self-organization of the plasma state, which has applications to fusion, complex systems, nonlinear dynamics, and astrophysics.

- **TOWARD STEADY-STATE BURNING PLASMA OPERATION:**
  Can the tokamak confinement concept be extended to the continuous, self-sustaining regime required for future power plants?
  Most magnetic fusion energy systems will need to operate with a continuous fusion burn for months or more at a time. A critical long-term question is whether the complex burning plasma state can be effectively manipulated with a minimum of external control in a tokamak plasma to provide a high-performance, steady-state burning plasma that is especially applicable to a fusion power plant. By creating moderate-gain burning plasmas

for several thousand seconds, ITER will enable an assessment of whether the physics and engineering requirements for continuous burning operation can be met in a tokamak-based power plant. This will require developing the tools needed to control and optimize burning plasmas at very high pressures, and an understanding of how these can be extended to future power plants. This becomes ever more challenging as operation in this regime increasingly relies on the self-organizing properties of the plasma to facilitate near-steady-state operation.

- **FUSION TECHNOLOGY:**
  What materials and components are suitable for the plasma containment vessel and its surrounding structures in a fusion power plant?
  Many materials and components comprising ITER will be subjected to high neutron fluxes born from fusion reactions. These may alter material properties and component behavior, and thereby potentially affect their properties and lifetime. Plasma-facing components will also be subjected to unprecedented amounts of heat and particles generated by the fusion reactions. Both issues present profound challenges for materials and engineering science and heat and particle flux management, which in turn can influence the plasma performance. Information obtained from ITER in these areas will be first-of-a-kind and will guide future decisions on fusion power plant construction and operation.

The overall goals of the research agenda for ITER consist of obtaining answers to these questions. Developing an understanding of the issues covered by these questions will generate the knowledge base for the next stage in the development of fusion energy. It should be noted that these questions will be answered to varying degrees of completeness in the ITER program. The first two should be fairly completely addressed in ITER. The third topic will require further extension to the higher power densities required for some power plant concepts. While several fusion technology issues will be confronted for the first time in ITER, some critical issues, such as component lifetimes under the high, integrated neutron exposure typical of a power plant, will necessarily remain for steps beyond the ITER experiment.

I.A.3 Research Community Structure

⇒ The burning plasma research program in the U.S. is being organized to maximize the scientific benefits of participation in the international ITER experiment.

⇒ Past investments in fusion research have positioned the U.S. Fusion Energy Sciences program to contribute to and benefit from participation in the ITER experiment.

Participation in the ITER program has been designated “the top priority in a balanced program” for the U.S. Fusion Energy Sciences program. It represents a major extension of the program’s research activity and presents an organizational challenge to the U.S. Fusion Energy Sciences program. Entry to the burning plasma research era will require reorientation of elements of the U.S. Fusion Energy Sciences program. Over time, these changes could be profound. However, they will be paced by developments in the international ITER Organization itself. The U.S. fusion research program is evolving to optimize its participation in this unprecedented international collaboration, and has already added a new organizational component to facilitate this evolution. A snapshot of programmatic structures in the U.S. Fusion Energy Sciences program created to support participation in the international ITER Organization is given here.

There are many ways by which the U.S. fusion research community will participate in the ITER research program. Some of these are defined in the formal ITER negotiated agreement. The international ITER Organization, in consultation with the national partner organizations, will determine many other issues. These include the interaction between the international ITER Organization and the U.S. Fusion Energy Sciences program, as well as the interaction among all partner research programs.

For the construction phase, the next ten years or so, the structure of the ITER Organization is presently being defined by the new Director General and Principal Deputy Director General. The U.S. ITER Project Office (USIPO) is the domestic agency that has responsibility for executing the U.S. contributions to the construction effort. The U.S. fusion research community interacts with the USIPO by executing short-term ITER Research Tasks, participating in specific Work Packages that are part of the U.S. responsibility in the ITER construction, and performing research in the U.S. Fusion Energy Sciences program that supports preparation for ITER construction and operation.

The U.S. fusion community will contribute researchers to the international ITER Organization during experimental operations. In addition, members of the community will also routinely participate as short-term visiting scientists. However, the size of the central ITER science team, number of visitors, etc. is yet to be finalized. In the meantime, the U.S. Fusion Energy Sciences program is organizing itself to adapt to most expected modes of collaboration.

A new U.S. Burning Plasma Organization (USBPO) was established in May 2005 to organize the U.S. fusion research community and provide technical input on any redirection of research activities needed to support burning plasma related research. It acts as an umbrella organization for coordinating relevant burning plasma research activities in the U.S. Fusion Energy Sciences program in support of ITER participation. Through the USBPO, U.S. scientists will identify possible new areas of focus or redirection of research activity that are needed for ITER participation or desired for extension of ITER capabilities, but not supported by the construction project.

The USBPO will provide technical support to the U.S. ITER Project Office to help resolve scientific or technical issues that arise during the construction effort. In that role, the USBPO helps coordinate and execute specific ITER Physics Tasks arising from the USIPO design and construction activities. To aid coordination between the USIPO and the research community, the USBPO Director is also the USIPO Chief Scientist. In a similar vein, the Director of the U.S. Virtual Laboratory for Technology, which coordinates fusion technology research in the U.S., is the USIPO Chief technologist.

The U.S. Fusion Energy Sciences program’s participation in the International Tokamak Physics Activity (ITPA) presently serves as the primary conduit between these U.S. research activities and international research. The ITPA has been the main international coordinating activity to support development of ITER physics and has facilitated joint experiments and facility sharing. The ITPA could evolve to be the technical link between the U.S. research program and the international ITER Organization, and strong links are being developed between the ITPA and the USBPO to optimize interactions with international colleagues. In addition, members of the U.S fusion community collaborate directly with international colleagues through a variety of multilateral International Energy Agency implementing agreements and through U.S. bilateral agreements with the European Union and other ITER partners.

Considerable progress has been made in the scientific understanding of most major issues needed to support access to the burning plasma regime for ITER. This progress has been especially pronounced over the past 10-15 years. For example, nonlinear instabilities in plasmas at high pressure, which could potentially limit performance in ITER, have been observed, explained, and experimentally stabilized. Plasma confinement properties have been related to complex, microscopic fluctuations in the plasma, and spinning the plasma has been shown to improve confinement by suppressing these fluctuations. Experiments in U.S. facilities are pointing the way toward more advanced operational regimes that may extend the performance of ITER to very long-pulse, near steady-state operation. These and many other developments directly support and optimize the abilities of the U.S. research community to both contribute to the success of ITER and benefit from participation therein.

Through its work in these areas, the U.S. historically has been recognized for its strong contributions to fusion energy science and technology and has made significant contributions to the ITER collaboration in its design. While it is expected that the financial contributions of the partners will be considered, the U.S. believes the research program planning should be based mainly on scientific merit. Within such a framework, U.S. researchers, like all partners, will have adequate opportunity to strongly influence the scientific program on ITER to accomplish its mission. To do so effectively, however, it will be necessary to maintain an excellent world-class fusion research program that can excel in this large, multi-partner international collaboration.

I.B Summary Responses to EPAct Plan Elements

I.B.1 Element 1: The U.S. research agenda for ITER

⇒ ITER will make major contributions to the U.S. research agenda for burning plasma studies in six major scientific themes, or campaigns.

⇒ Achieving the long-term scientific goals in ITER requires well-defined, long-term R&D activities in each of the priority science areas. These efforts span from the present design support stage to the final high-power, long-pulse technology test stage of ITER operation.

A comprehensive scientific understanding of the burning plasma state is needed to confidently extrapolate plasma behavior and related technology from ITER to a fusion power plant. Developing this predictive understanding is the overarching goal of the U.S. Fusion Energy Sciences program. The concept of a predictive understanding will of course evolve as the ITER project evolves. In the near-term, it refers to the ability to predict the plasma behavior in the new regimes in which ITER will operate. In the longer term, it refers to the ability to use the new knowledge gained in ITER to reliably predict plasma behavior in next-generation energy-producing facilities. The U.S. agenda for research on ITER therefore focuses on developing and testing the basic understanding of burning plasmas and their interactions with the surrounding materials. Details of the U.S. agenda for research on ITER are presented in Chapter II, while an overview of this agenda is presented here.

The U.S. research agenda for ITER is designed to develop answers to the aforementioned fundamental questions posed for ITER. It implicitly includes the broad ITER goals and requirements, plus the long-term goal of building a fusion power plant. Recent reviews of the U.S. Fusion Energy Sciences program and community studies have provided rich sources of input for developing a U.S. research agenda for participation in the international ITER Organization. These include, among others: two recent National Academies studies of the U.S. Fusion Energy Sciences program [1,2]; several Fusion Energy Sciences Advisory Committee (FESAC) reviews on Burning Plasma science and ITER [3,4,5]; a recent FESAC Scientific Priorities study [6]; a FESAC review of the major facilities in the U.S. [7,8]; ongoing participation in the International Tokamak Physics Activity; interaction with the U.S. ITER Project Office and the international ITER Organization; and, most recently, a community Burning Plasma Workshop for identifying near-term burning plasma research activities. These sources are being used in the evolution of the research agenda for burning plasmas on ITER.

The agenda for research on ITER consists of a number of long-term, specific research goals that need to be achieved during ITER operations. Achieving these goals collectively develops answers to the fundamental questions posed earlier. These goals are embedded in specific scientific campaigns that cover the breadth of science and technology issues arising in the quest for fusion energy. This agenda is represented by a conceptual timeline for the flow of research activity that is shown in Figure 1.1. It contains two main elements: 1) the general time frames over which the four fundamental questions are expected to be addressed; and 2) the specific science campaigns around which the U.S. fusion research program is organized to confront these questions and the stages of development through which each campaign evolves.

The ITER research program, as defined by the international design team, can be divided into four sequential phases in time, ranging from the present through the experimental operations on ITER. These set the expected timeline for ITER, and are indicated at the top of the chart:

- *Design Support and Pre-operation*
- *Commissioning and Initial H, D (Non-burning) Operations*
- *High Gain DT (Burning)*
- *Modest Gain DT, Long Pulse, Non-Inductive*

I.B.1.a Science and Technology Campaigns

Following recommendations from the National Academies Burning Plasma Assessment Committee, the U.S. fusion science program has been organized around six major scientific and technological campaigns to cover the breadth of issues involved:

1. *Integrated Burning Plasma Science (i.e., Studying the complex interactions of fusion physics phenomena)*
2. *Macroscopic plasma physics (Stability)*
3. *Waves and Energetic Particles (Heating, plasma control, and effects of fusion products)*
4. *Multi-scale Transport Physics (Confinement)*
5. *Plasma Boundary Interfaces (Interfacing the burning plasma with the container)*
6. *Fusion Engineering Science (Fusion tools and technology)*

The research agenda for U.S. participation in ITER is mapped to these six campaigns. Progress in all six will enable the U.S. to participate fully in developing the scientific basis for predicting and optimizing ITER performance and for identifying requirements for optimizing the next step beyond ITER.

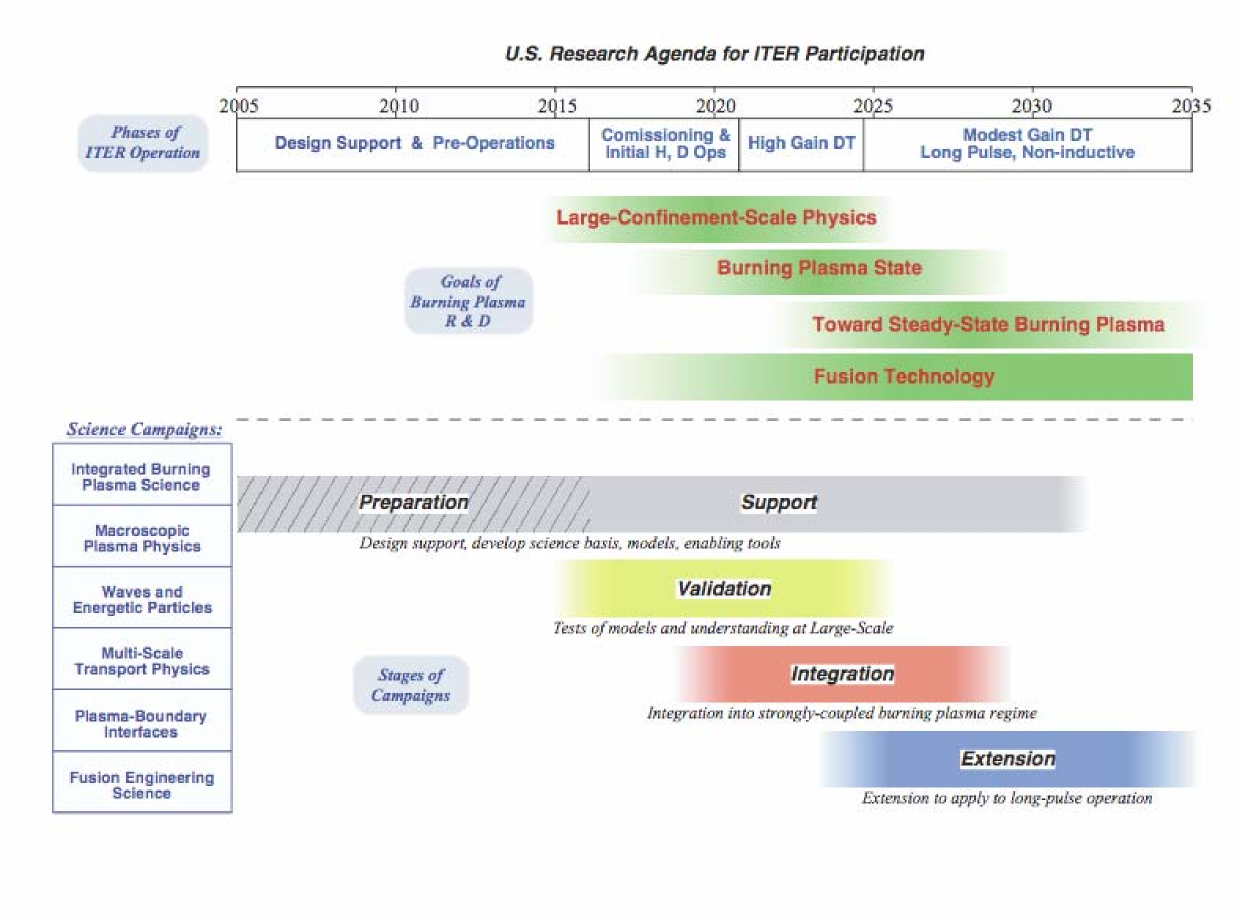

Figure 1.1. Conceptual timeline for U.S. Research Agenda for ITER Participation.

Each science campaign in the U.S. fusion program contains two or more long-term goals for the ITER program that need to be addressed to either assure successful operation of the ITER experiment and/or develop a predictive understanding of the fusion plasma environment. As examples, these cover topics such as plasma instabilities that limit the pressure in the fusion device, processes that determine the loss rate of energy from the device, complex interactions between the hot plasma and the surrounding containment vessel, and technology required to deal with the intense neutron environment found in a burning plasma experiment.

Details of this agenda are discussed in Chapter II, where specific goals of research in ITER are identified for the various phases of the ITER program and a timeline for addressing each specific goal related to each topic is indicated. Planning backwards from each long-term goal identified for ITER operation, the required preparation activities are readily identified. These include developments in theory and modeling, as well as enabling technologies such as new plasma diagnostics. It is critical that the evolving understanding of all topics be experimentally validated as much as possible by studies in available smaller facilities before application to the integrated, and hence more complex, ITER environment.

In Fig. 1.1, these six scientific campaigns evolve through generic levels of development including: *preparation* for experiments on ITER; *validation* of understanding of the physics at power plant-scale; *integration* of relevant physics in the strongly-coupled burning plasma regime; and finally *extension* of the knowledge gained from ITER and support experiments to very long pulse for the next step in the development of fusion energy. This figure is strictly illustrative; campaigns to achieve specific goals in the agenda will be at varying degrees of development at any given time. In practice, there will be a need for preparatory activities throughout the ITER program. This is especially true because almost every experiment undertaken on ITER will require extensive modeling and validating tests on smaller facilities in order to justify an allocation of run time.

While most of the topics presented in the detailed research agenda are part of the baseline ITER program, there are areas of interest to the U.S. research community that may require extensions of ITER capabilities beyond the initial baseline. This may include increased diagnostic capabilities, additional heating and current drive tools, etc. Such extensions are typical of scientific experiments. They will develop from discussions with the international partners and are likely to evolve as the ITER program evolves. Those topics that involve extensions beyond the baseline design are indicated in the discussion of specific topics.

It is important to note that throughout the entire U.S. research agenda for ITER there is a very high potential for ***discovery science***, wherein new ideas and paths of inquiry arise as experiment and theory confront one another. This is characteristic of the research throughout *the entire* program, but it will be especially true for the strongly-coupled burning plasma regime, where the highly nonlinear nature of the interactions could result in new modes of behavior being discovered. This potential for new discoveries does not readily show up on a schedule for a planned U.S. research agenda for ITER. Rather, its influence is reflected in changes to the expected program that arise due to new discoveries.

I.B.1.b The Near-term U.S. Agenda for ITER Participation

There is need for research both in the decade before and during actual operation of the ITER experiment, and for continuing research on other devices, to support ITER research objectives. To that end, the U.S. research program will provide ongoing research that is directed both toward maximizing the research output of ITER and building the scientific basis for advancing fusion energy to the next step beyond ITER. This effort will take advantage of U.S. device flexibility to: develop and optimize ITER operating scenarios; extend these scenarios to larger facilities abroad through collaborative joint experiments; exploit the superior access of these non-burning-plasma experiments to develop diagnostics and control techniques for later ITER deployment; and further advance fusion engineering science to develop better plasma control tools and prepare to participate in the ITER blanket test program. This research will comprise the burning plasma research activity of the U.S. fusion research program.

A first list of activities needed to prepare for ITER participation is given in the specific goals and preparatory studies described in Chapter II. Programs in theory and computational modeling are helping the development of critically needed integrated models of plasma behavior in the tokamak. The large confinement experiments (DIII-D and Alcator C-mod tokamaks and the NSTX spherical torus) will: develop advanced tokamak operational regimes for both extended ITER operation and future power plant concepts; measure and test theories of the complex turbulence that determine energy confinement properties; actively control high-pressure plasma instabilities; test plasma-wall interactions and energy flux handling at levels expected in ITER; and study energetic particle influences on plasma stability in regimes close to those expected in burning plasmas in ITER. This list is representative from a recent FESAC Facilities Review, and is not exhaustive. Historically, the U.S. research community has also developed many new innovative diagnostic measurement techniques that may extrapolate to ITER conditions.

I.B.1.c Toward Prioritization of Research Agenda Elements

The international ITER Organization will necessarily decide the plans for ITER operation, and the timelines are shown herein to indicate the general flow of expected activity. The U.S. research agenda for ITER participation will evolve in parallel with the international plan.

A prioritization of the U.S. research agenda for ITER is needed, and that process is beginning. In the research tasks in preparation for ITER and the research goals to be achieved on ITER identified in Chapter II, the Burning Plasma Organization has selected what it feels are the highest priority tasks. A certain level of prioritization can also be inferred from the relative timing of specific goals and tasks identified. The tasks selected are those for which the U. S. fusion program is positioned to make important and often unique contributions. However, it is important to note that the detailed research agenda presented here is an initial concept only, and should be expected to change as this project moves forward. The U.S. Fusion Energy Sciences program will need to work with the other ITER partners to identify which of these topics should be emphasized by the U.S. fusion research program in the next decade or so.

It is also clear that choices will need to be made concerning where to concentrate U.S. assets to develop a leadership position in certain areas for support of ITER and fusion development. In those areas where the U.S. will not have sufficient resources to maintain a leadership position, it will be important to define the level of activity required to contribute and maintain the expertise needed for steps beyond ITER.

To refine U.S. activities and plans for ITER participation and continue developing a prioritization of activities in the U.S. research agenda for ITER, a planning activity will be pursued within the U.S. Burning Plasma Organization. This will engage the research community to expand this initial planning exercise to consider the tasks to be addressed in the U.S. burning plasma research program. The balance of activities pursued in the U.S. research agenda for ITER, plus additional activities such as collaborating on international facilities as appropriate, will be periodically evaluated by OFES, in consultation with FESAC. An ongoing dialog with the international partners will be integrated into these planning activities.

I.B.2 __Element 2__: Methods to evaluate whether ITER is promoting progress toward making fusion a reliable and affordable source of power

⇒ Progress on critical scientific and technology issues needed to design future fusion energy power plants will be evaluated with metrics based on increased scientific understanding and on performance in the burning plasma regime.

⇒ The research plan toward the fusion goal should be periodically assessed and modified by internal and external reviews.

A number of fusion power plant studies have identified the major scientific and technological goals for an attractive fusion power plant. These include operational, economic, safety, and environmental goals. Tracking progress toward these goals provides two types of metrics relevant to evaluating progress in ITER; one measures progress in scientific understanding, and the other measures progress in burning plasma performance.

I.B.2.a Scientific Progress

The first class of metrics addresses the need to measure scientific progress in critical plasma physics and technology issues. A relatively straightforward metric for progress in scientific understanding consists of evaluating whether the specific goals in the detailed research agenda discussed above are achieved in the expected time frame. An important example pertains to confinement and transport: the ultimate goal of understanding transport in the burning plasma regime requires developing an understanding of electron energy losses and creating an integrated transport model for the electrons and ions in the plasma. A second example would be a controlled challenge of expected confinement-limiting stability boundaries in ITER to verify the predictive capability of existing theory. The level of agreement among theory, simulation, and experiment readily measures progress toward these goals.

Another measure of scientific progress is the ability to use that knowledge to extend plasma performance toward that needed for fusion power. Examples include development of plasma control tools to create advanced tokamak operating modes to improve ITER plasma performance and allow an expanded fusion technology mission for ITER. Another example includes tool development for disruption mitigation and avoidance – a key issue for a reliable and affordable tokamak-based fusion power plant. A metric on disruption control would assess the readiness of such tools and the underlying theory for application in ITER plasmas by assessing their robustness from applications on devices elsewhere in the U.S. and world fusion programs. Successful application on ITER would not only enhance the capability of ITER, but would resolve a key issue for a tokamak-based magnetic fusion power plant.

I.B.2.b Energy and Technology Progress

The second class of metrics pertains to system performance. This class uses figures of merit based on integrated technical achievements. These rely on specific quantitative measures of the performance of the fusion system. They include fusion power, sustained fusion gain, and pulse length of burning ITER plasmas. Technology metrics will also be developed for the period of operation prior to the generation of the first deuterium-tritium burning plasmas. Many of these will be able to be linked with a particular calendar date on the ITER program timeline, providing simple measures of progress that will be readily communicated both inside and outside of the fusion research program.

Progress in achieving the plasma performance needed for a fusion power demonstration plant (DEMO) is readily measured by comparing key performance parameters achieved to date to those expected in ITER and those required for a conceptual DEMO power plant. These include: fusion power, fusion power gain, plasma pressure, power density, power dissipation, and neutron wall loading. Comparison of these parameters achieved in ITER to those required for DEMO provides an array of objective measures of the progress toward fusion power.

Overall, measurements of the effectiveness of the U.S. participation in ITER can include: number of U.S. scientists and engineers participating in ITER; the number of experiments and technology tests proposed or led by U.S. participants; achievement of science and technology goals on ITER; number of research publications; citations of U.S. research publications; and achievement of high-level milestones for burning plasma research identified as part of the Administration's Program Assessment Rating Tool.

There is a tendency to give greater weight to the relatively simply defined performance metrics while downplaying metrics that track progress in developing the scientific understanding of the burning plasma state. However, the focus of the U.S. Fusion Energy Sciences program is the development of the underlying science of the fusion plasma system to provide the tools needed to move beyond ITER to the fusion power goal. Hence, measurements of scientific progress are the more important metrics in evaluating progress in the ITER participation. In that context, the performance metrics simply measure progress toward attaining the appropriate conditions for testing knowledge of the underlying science.

The ultimate measure of progress in scientific understanding consists of periodic peer review of the research activities performed. An important feature of the U.S. involvement in ITER will thus be the periodic assessment of scientific progress on ITER and toward fusion energy by internal and external peer review. This process could include reviews by leading researchers in physics and technology disciplines inside and outside of the fusion realm, as well as by representatives from energy utilities and industrial and environmental communities when the energy goal becomes more immediate.

I.B.3 Element 3: Description of how work at ITER will relate to other elements of U.S. fusion research program

⇒ A program of configuration optimization, enabling technology, and predictive simulation, supplementing ITER, ensures that the U.S. will have an adequate knowledge base for developing an attractive fusion power source beyond ITER.

ITER will take magnetic fusion deep into the burning plasma regime and move significantly closer to the fusion energy goal. However, the comparison between ITER and prototypical power plant parameters makes clear that further advances will be needed beyond ITER. The NRC Burning Plasma Assessment study presented four goals that must be pursued in parallel with burning plasma studies in ITER to move toward attractive fusion energy:

- *Maximize the plasma pressure*
- *Maximize the energy confinement*
- *Minimize the power needed for sustainment*
- *Simplify and increase reliability of the chosen confinement concepts.*

The U.S. is addressing these goals with a science-based strategy that aims to broaden the understanding of fusion science and technology and thereby establish the knowledge base and tools needed to determine the next steps beyond ITER.

This strategy includes large programs in four magnetic configurations (the advanced tokamak, spherical torus, stellarator, and reversed field pinch), enabling technology, theory and computation, and a portfolio of small-scale experiments examining emerging concepts in magnetic confinement science. Through participation in ITER, the U.S. will obtain the burning plasma knowledge that is needed, in combination with the magnetic configuration knowledge base from the U.S. portfolio described here, to establish a path for practical fusion energy beyond ITER. Predictive understanding, embodied in theory and simulation codes, is a key to making this possible.

The advanced tokamak (AT) is a variant of the tokamak that has the aim of extending the performance of tokamaks beyond their currently understood limits and developing means to sustain tokamak plasmas for indefinite durations. The AT physics strategy uses active control of the internal plasma properties and special magnetic coils to maintain a stable configuration with good performance. As the plasma performance is increased in this advanced regime to those desired for the next step beyond ITER, the plasma enters an increasingly self-organized state, wherein its intrinsic properties determine its stability and performance. This becomes even more pronounced in a burning plasma with strong self-heating, and new tools and approaches to plasma control will be needed to exploit advanced tokamak operation at power-plant-relevant parameters.

Spherical Torus (ST) research addresses the possible benefits of shrinking the hole in the middle of the torus as much as possible. The study of ST plasmas is of interest because it challenges tokamak-based physics understanding at the limits of shaping and thereby provides an additional perspective on the scientific issues encountered in ITER. It allows access to stable high-pressure regimes, and enables unique studies of the interactions between energetic particles and plasma waves, an issue of high importance to ITER. A sustained ST configuration may form the basis for a relatively compact fusion system for component performance and life testing. It could thus support the development of fusion power plant technologies needed for the step after ITER, providing a reduced-cost path to fusion energy development.

The stellarator is a toroidal configuration in which the magnetic fields needed for plasma confinement and stability are generated by external coils with complex shapes. This allows very efficient steady-state operation and greatly reduced susceptibility to current-driven instabilities that can disrupt the plasma. The near-term U.S. focus is to test the predicted benefits of a class of compact stellarators that include the benefits of three-dimensional shaping for a passively stable fusion plasma solution. Its magnetic symmetry provides a high degree of physics overlap with tokamaks, so stellarator development can proceed based on the burning plasma knowledge gained from ITER. As a potential fusion development path the stellarator offers a fusion system with reduced plasma control requirements and improved reliability.

The reversed-field-pinch (RFP) is a toroidal configuration wherein the magnetic fields are generated mainly by internal plasma currents. It offers potential advantages, and provides a scientifically interesting contrast with configurations, such as the stellarator and tokamak, whose magnetic fields are generated mainly by external coils. An understanding of the physics underlying magnetic field generation through plasma currents is critical to the success of the RFP. Through research on this topic, the fusion energy community has established vital links in the astrophysics community, where equivalent physics is of central importance to solar dynamics.

The U.S. Fusion Energy Sciences program also includes a modest number of small-scale experiments designed to examine basic plasma science and emerging concepts in magnetic confinement. In addition to supporting the development of plasma physics and expanding the knowledge of magnetic confinement physics, these programs support education and help develop the future workforce for fusion energy development, like the rest of the U.S. Fusion Energy Sciences program.

The U.S. will use the knowledge gained in ITER burning plasma experiments to predict performance in other toroidal confinement configurations that are candidates for fusion energy development beyond ITER. Since such knowledge transfer will require a detailed theoretical understanding of the fundamental physical processes involved, the U.S. is carrying out a program to develop a first-principles understanding of the phenomena that determine ITER's performance. The continued development of improved computational models of the edge plasma, transport barriers, density limits, core confinement, MHD instabilities, heating, and wave-plasma interactions will enable the U.S. Fusion Energy Sciences program to gain the most from its participation in ITER. An additional benefit is the ability to transfer understanding across the portfolio to illuminate related phenomena in tokamaks, especially in the burning plasma stage. Going forward, developing the capability for predictive simulation relies on a merger of advances in plasma science, information technology, applied mathematics, and software.

II The U.S. Research Agenda for ITER

The highest-level purpose of ITER is "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes."[9] It will do that by producing a nominal 500 million Watts of fusion power in 400-second pulses. It will enable the creation of a burning plasma with an energy gain Q (the ratio of fusion power produced to external power applied to heat and control the plasma) of ten, sufficiently high that the plasma is dominantly self-heated by the alpha particles. The high fusion power and plasma temperature in ITER also enables the alpha particle pressure to be a significant fraction of the total plasma pressure, a key factor in enabling study of the new physics to be encountered in a burning plasma.

Secondary technical objectives of ITER [9] are:

- achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary heating power of at least 10 for a range of operating scenarios, and with a duration sufficient to achieve stationary conditions on the timescales characteristic of plasma processes, whilst not precluding the possibility of controlled ignition;
- aim at demonstrating steady-state operation using non-inductive current drive with the ratio of fusion power to input power for current drive of at least 5.;
- demonstrate availability and integration of technologies essential for a fusion reactor;
- test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat, and electricity production.

ITER will develop and test technology critical for the advancement of fusion research. Its all-superconducting magnet technology and steady-state heat removal technology will enable developing the basis of steady-state plasma operation and high-energy gain in future fusion systems. Its extensive measurement and control systems that allow variation of the plasma state, and long pulse capability will enable understanding of the burning plasma state.

This chapter lays out the anticipated U.S research agenda for ITER. It is organized around the scientific campaigns identified in the FESAC report "Scientific Challenges, Opportunities, and Priorities for the U.S Fusion Energy Sciences Program [6], with the addition of a campaign to study the integrated burning plasma system. More details on the technical elements can be obtained in that report. Due to its capability to access and study a burning plasma, ITER will make unique scientific contributions in each of these campaigns. In support of these experiments, the on-going U.S. research program is addressing key preparatory scientific issues and preparing U.S. participation in executing the research program on ITER.

Figure 2.1 shows the research plan anticipated for ITER. Under the timeline are phases of development for the ITER program as defined by the ITER Project[9]. Down the left hand side are the major scientific campaigns. Scientific goals for ITER (in red) and their corresponding preparatory research elements (in black) are presented.

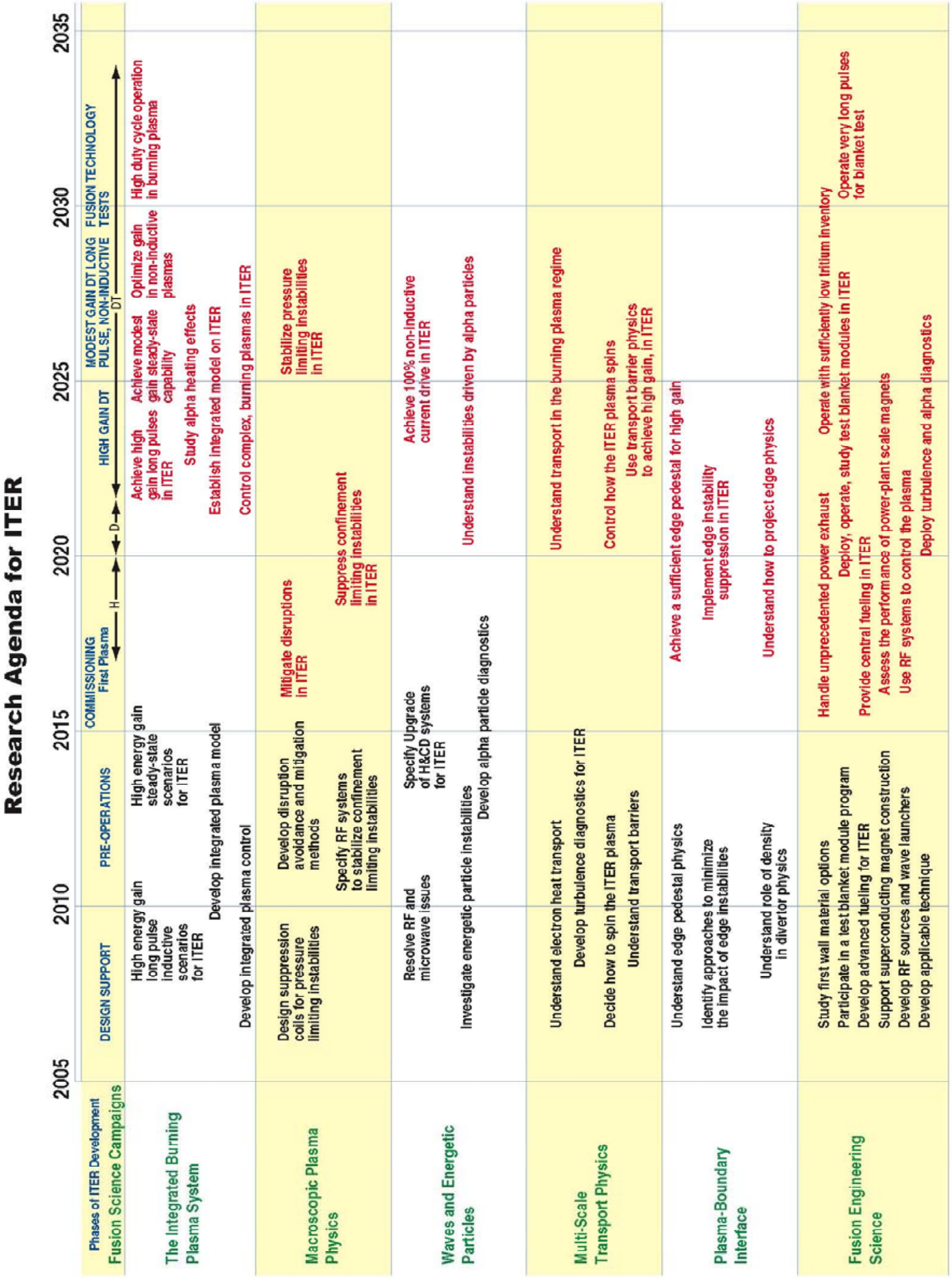

Figure 2.1. Anticipated U.S. Research Agenda for ITER. Green headings (left) are major scientific campaigns. Across the top are the phases of development of ITER operation. Black text denotes U.S. fusion research program objectives to prepare for research on ITER. Red text denotes research objective to be pursued on ITER.

Specific ITER research goals for each of the major research campaigns and required preparatory work are given in the following discussions. An overarching goal is developing an understanding of the complex, interrelated processes that govern the dynamics and set the control requirements of the burning plasma state. The understanding sought and demanded of ITER research has two components. First, where possible, demonstrating understanding will require validation of theories by comparison with measurement of the fundamental underlying processes that determine the plasma state and govern its dynamics. Second, a predictive capability of burning plasma characteristics and evolution shall be demonstrated using models built upon these validated theories. Where empirical models are required, they shall be validated against experiment over as wide a range of parameters as possible so as to ensure their reliable extrapolation to future burning plasma devices.

II.A Integrated, Burning Plasma System Campaign

The essential challenge of the ITER experiment is to successfully manage the complex integration of all the fundamental physics elements of fusion so that a stable, steadily burning plasma state is achieved. The burning plasma is replete with complex internal feedback loops and couplings (see Figure 2.2). The dominant internal source of heat in the plasma will be from alpha particles produced in the fusion reactions, and the spatial distribution of that heat source will depend on the spatial distribution of the plasma pressure. But the pressure distribution itself is determined by the dominant alpha particle heat source and external sources of heat and particles and the spatial profiles of the plasma turbulence. The plasma turbulence is in turn determined by the gradients of the plasma temperature and density and is also profoundly affected by the spatial distributions of magnetic and electric fields. The alpha particles themselves may promote or deteriorate the stability of the plasma, perhaps causing loss of the alpha particles and their vital heating effect. Only in ITER can instabilities actually driven by the alpha particles be studied comprehensively, although present day experiments can partially explore this physics with surrogate energetic particles from beams or rf heating. Studying the complexity of this coupled physical system will be a principal area of research in ITER and the preparatory research leading up to ITER operation.

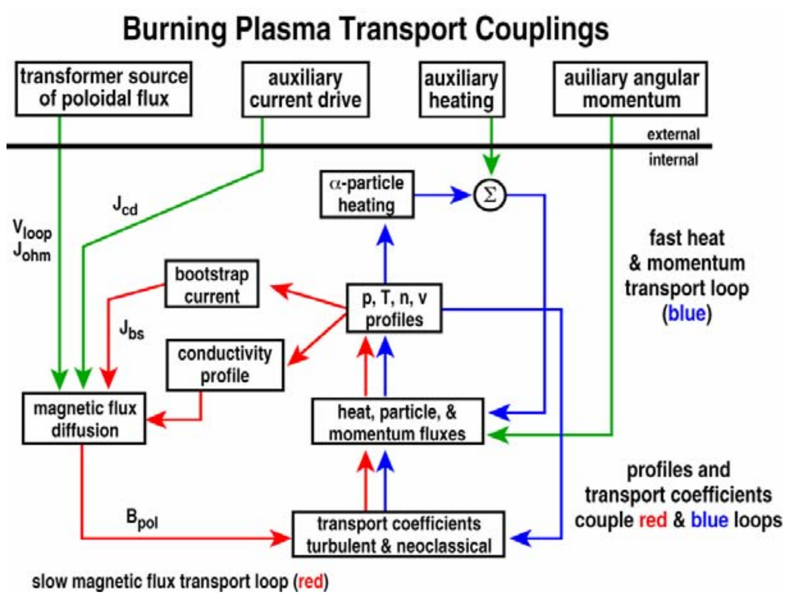

Figure 2.2. Illustration of complex feedback loops and non-linear couplings among basic plasma phenomena that result in the final burning plasma state.

Goals on ITER: ***Study alpha heating effects***
Achieve high gain in ITER
Control complex, burning plasmas

ITER Time Frames: ***High Gain DT***
Modest Gain, Non-inductive Phase

Preparatory Research: ***Develop high-energy gain long pulse inductive scenarios for ITER***
Develop integrated plasma control

ITER will be the first magnetic fusion device to study burning plasmas in high gain discharges in pulse durations of 400s. The rapidly evolving state of current worldwide research suggests that it should be possible to extend the pulse duration to about one hour at high gain in ITER and thereby establish the scientific basis for steady-state plasmas (see eventual goal for high gain, steady-state capability in ITER in Figure 2.1 and prior stepping-stone goals). To accomplish this, plasma pressure limits must be increased to simultaneously achieve high gain and a high fraction of self-driven plasma current. A high self-driven current fraction enables the achievement of steady state operation with a tractable amount of auxiliary power driving the remainder of the plasma's current. Success in this effort could advance ITER's research progress by some years. The leverage of the present U.S. research program is extremely high here. Only U.S. experiments are equipped to tackle the necessary increases in the plasma pressure limit and thus the U.S is in a world leading position in high gain, steady-state plasma research.

Goals on ITER: ***Achieve modest gain steady-state capability***
Optimize gain in non-inductive plasmas

ITER Time Frame: ***Modest gain, Non-inductive Phase***

Preparatory Research: ***Develop steady-state, low-driven-current scenarios for ITER***
Extend integrated plasma control

A key research goal for ITER is the development of a comprehensive validated integrated simulation model for a burning plasma. Such a model will not only provide a predictive capability of burning plasmas, but will enable a critical analysis of experimental scenarios prior to experimental operation to assure optimal use of valuable machine time. The status of computational models today is that they successfully describe important individual physical phenomena. The cutting edge effort now is to combine this body of knowledge into ever more integrated computational models, so that the complexity of the total, integrated system can be exhibited in simulations. The development and validation of such an integrated model will be a major challenge for the world theory and modeling community in the next ten years (see Figure 2.1) in preparation for ITER operation.

Goal on ITER: ***Establish integrated simulation model***

ITER Time Frames: ***Commissioning***
High Gain DT Phase
Modest Gain, Non-inductive phase

PreparatoryResearch: ***Develop integrated plasma model***

II.B Macroscopic Plasma Physics Campaign

The design of ITER builds upon the understanding of plasma instabilities developed from existing tokamak experiments, including methods to increase the pressure limits using plasma shaping, control of plasma profiles, and external feedback systems. The research goal for ITER is to test this understanding at larger effective plasma size (i.e., power-plant scale) and in the presence of a substantial alpha-particle population. This understanding can provide the basis for increasing the plasma pressure and hence the fusion power in ITER and for fusion power generally.

Pressure-Limiting Instabilities – The pressure limit in tokamak plasmas is determined by a combination of long and short wavelength instabilities. Since ITER was designed, recent experiments in the U.S. have confirmed a theoretical expectation that a metal wall close to the plasma surface and suitable feedback coils can almost double the standard pressure limit. Since the required coils or other technologies may have to be built into the basic ITER machine design, ITER is very interested now (see first goal in this area in Figure 2.1) in information on how to achieve such increases in the pressure limit. Continued research is urgent to provide the necessary guidance to ITER. The U. S has a unique position in this research.

Goal on ITER:	***Stabilize pressure-limiting instabilities***
ITER Time Frame:	***Modest gain Non-inductive Phase***
Preparatory Research:	***Define suitable control coil systems for ITER***

Confinement-limiting Instabilities – The achievement of ITER's nominal objective of 500 MW for 400 seconds may require the stabilization or avoidance of certain instabilities that reduce the confinement quality of the plasma. Methods of doing so have been developed in present day research, employing microwaves to drive very localized currents in the plasma. Continued research is needed (second goal, Figure 2.1) to specify the microwave or other systems to stabilize or avoid these modes. Because the required technologies are auxiliary systems that can be altered later, the time scale for this information is not quite so urgent as for the pressure limit.

Goal on ITER:	***Suppress confinement limiting instabilities in ITER***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Specify RF systems to stabilize confinement-limiting instabilities***

Disruption Avoidance and Mitigation – Plasmas that hit the pressure limit suffer an abrupt loss of thermal energy and plasma current (a disruption), which entails high risk of damaging components inside the vacuum vessel. Due to the size and energy stored in the ITER plasma, new phenomena are anticipated. Experiments have recently shown the ability to mitigate the consequences of disruptions with massive injection of noble gases. Such a system or similar system should be in place on ITER for initial operation (just after 2015 in Figure 2.1). The required technology is inexpensive and straightforward to deploy, but further research is needed to develop an understanding of these mitigation techniques, methods to recognize when mitigation is necessary prior to an event, and control systems that can maintain a plasma reliably close to the pressure limit.

Goal on ITER:	***Mitigate disruptions***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Develop disruption avoidance and mitigation methods***

II.C Waves and Energetic Particles Physics Campaign

Electromagnetic waves (i.e., microwaves) and energetic particles are used to heat and drive currents in the plasma. ITER offers a unique opportunity to study confinement of the energetic alpha particles created by the fusion reactions and the heating of the background plasma by alpha particles. Since the alpha particles can interact with the background plasma in complex ways, a key research goal for ITER is to demonstrate and understand alpha-particle heating in regimes of high gain. This understanding is critical for fusion energy since the uncontrolled loss of alpha particles can result in damage to first wall components and increases the energy required to sustain a burning plasma.

Energetic-particle-driven Instabilities – Alpha particles have a mean energy that is about 100 times greater than the plasma temperature and a significant partial pressure. They introduce new stabilizing and destabilizing properties (which may reduce fusion gain). While these issues have been studied in present day devices using externally generated energetic ions, the space and energy distribution of the alpha particles and the spectrum of their driven instabilities will be different in the ITER burning plasma, possibly increasing alpha-particle losses. Alphas can also raise instability limits that increase the limit of plasma pressure that can be achieved, possibly leading to strong relaxation events. A modest level of alpha particle destabilization of intrinsic plasma waves may serve as an important diagnostic of alpha interactions. Severe instabilities can cause direct energetic alpha particle loss that could damage the first wall. It is important to establish the likely limits to the alpha particle pressures that can be confined. Research tasks for the next ten years (first two goals in this section of Figure 2.1) must include continued experiments with energetic ions simulating alpha particles and theory and code work to prepare for research on ITER. In addition, creative new measurement systems for the alpha particles and the instabilities they may drive need to be developed.

Goal on ITER:	***Understand instabilities driven by alpha particles***
ITER Time Frames:	***High Gain DT Phase***
	Modest gain, non-inductive Phase
Preparatory Research:	***Investigate energetic particle instabilities***
	Develop alpha particle diagnostics

Heating and Current Drive – The initial set of auxiliary heating and current drive systems on ITER was envisioned mainly to heat the plasma to achieve high fusion gain. To achieve the objective in ITER of 100% non-inductive current drive circa 2025 (Figure 2.1), about half the plasma current will be driven by RF and particle beam systems. These same systems must control the radial distribution of the plasma pressure to enable the other half of the plasma current to be self-driven. A potential upgrade of the ITER heating and current drive systems to 130 MW will probably focus on more current drive power. Ongoing research must resolve certain issues concerning the coupling of RF and microwave power into the plasma (first goal in this area, Figure 2.1). The decision on the requirements of particle beams will require resolving whether to provide more current drive or more momentum input to spin the plasma. Results from ongoing experiments, along with initial results from ITER, will provide the basis for deciding on the required auxiliary upgrade systems (second goal, Figure 2.1).

Goal on ITER:	***Achieve 100% non-inductive operation of ITER***
ITER Time Frame:	***Modest Gain, Non-inductive Phase***
Preparatory Research:	***Specify heating and current drive system upgrades for ITER***

II.D Multi-scale Transport Physics Campaign

Transport from Turbulence in the Unique Burning Plasma Regime – Burning plasmas in ITER must be in the regime of a low ratio of ion-gyroradius-to-system-size, the appropriate dimensionless scale size of a burning plasma. No current machine can operate in this power-plant-relevant regime. Such plasma operation at high plasma temperature is predicted to modify many phenomena already studied in existing experiments. Thus a key research goal for ITER is the study of transport and turbulence in high gain plasmas (top two goals in this area, Figure 2.1). These phenomena can determine the plasma pressure that can be confined and thus the level of fusion power produced.

In particular the energy transport carried by the electrons in ITER may be the most stringent confinement limit. Present day experiments are providing an understanding of transport from turbulence and are developing novel measurement capabilities, which are critically needed for ITER. Experiments on ITER will enable the extension of this research to study a burning plasma.

Goal on ITER:	***Understand transport in the burning plasma regime***
	ITER Time Frames: Commissioning Phase
	High Gain DT Phase and following Phases
Preparatory Research:	***Develop turbulence diagnostics for ITER***
	Understand electron heat transport

Plasma Spinning – Spinning the plasma in the torus is an important component of raising the pressure limit and can also increase the confinement. A better understanding of what makes plasmas spin is required for ITER, and more momentum input may be needed (eventual goal in Figure 2.1). This research must be done in current machines to enable ITER to be configured with the right hardware.

Goal on ITER: ***Control how the ITER plasma spins***
ITER Time Frame: ***High Gain DT Phase***
Preparatory Research: ***Decide how to spin the ITER plasma***

Transport Barriers – Suppression of turbulence in ITER can result in regions of exceptionally good confinement and may enable higher energy gain. Transport barriers in ITER will be produced by a combination of plasma spinning and compression of the magnetic field on the outboard side of the plasma. Continued research on transport barriers (last goal in Figure 2.1) is important in preparation for ITER.

Goal on ITER: ***Use transport barrier physics to achieve high gain***
ITER Time Frame: ***Commissioning phase leading to High Gain DT Phase***
Preparatory Research: ***Understand transport barrier physics.***

II.E Plasma-Boundary Interfaces Campaign

An energy-producing fusion system must not only generate sufficient fusion power, it must also exhaust the helium ash and absorb the generated energy at the walls of the device without deleterious effects. The heat flow to the divertor must be reduced using impurity radiation, but these impurities must not be allowed to transport into the core plasma where they would reduce fusion reactivity and increase radiative losses. Futhermore, the materials used must be compatible with tritium and the fusion-produced neutron flux. A key research goal for ITER will be to explore this challenging issue at the larger scale and power level of a burning plasma. For a fusion energy system, the maintenance requirements for the plasma facing components and the fusion power produced will be determined by resolving this complex set of issues.

The Edge Pedestal – A first-principles understanding of the structure of the edge region (i.e., pedestal) must be developed to underpin ITER fusion gain projections and solve the issue of pulsed heat loads from the plasma edge (first goal in this area, Figure 2.1). A transport barrier forms in a few centimeters just inside the edge of the confined plasma. In that region, turbulence is dramatically suppressed by plasma spinning, and the plasma pressure rises steeply onto an edge pedestal. But unknown physics limits the radial penetration of this transport barrier and must be resolved in current research. U. S. facilities are well equipped to explore this area.

Goal on ITER: ***Achieve a sufficient edge pedestal for high gain***
ITER Time Frame: ***Commissioning Phase***
Preparatory Research: ***Understand edge pedestal physics***

Edge Localized Modes – The high edge pressure gradient leads to regular periodic instabilities at the plasma edge. These modes (called Edge-Localized Mode, or ELM) have a modest impact on plasma facing components in current experiments, but in ITER the energy content of each ELM pulse may lead to excessive erosion of divertor surfaces and short replacement times. This sets up a fundamental conflict between the desire for a high edge pedestal for high-energy gain and the large ELM pulses that often result from a high edge pedestal. Continued research is vital to finding a solution to this conflict. In the U.S tokamaks, regimes with no ELMs have been found. ITER is very interested now (urgent goal in this area, Figure 2.1) in designing the kind of control coils needed in one approach to such a regime, since such coils may have to be included in the basic machine design. Research in this area is urgent and the U.S has a unique role.

Goal on ITER:	***Implement edge instability suppression in ITER***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Identify approaches to minimize the impact of edge instabilities***

Edge Plasma Physics – ITER will provide a unique opportunity to study the physics of the plasma edge at both a high absolute density and high absolute temperature (see last goal for ITER in this area, Figure 2.1). This combination can lead to new physical phenomena in the plasma edge region, but no current research device can do both simultaneously. Current research devices in the U.S can span the range of possibilities from ITER's high temperature, low density case up to ITER's high density case to provide comprehensive data for projection to ITER.

Goal on ITER:	***Understand how to project edge physics between devices***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Understand the role of density in divertor physics***

II.F Fusion Engineering Science Campaign

The fusion energy sciences program requires the development and deployment of various tools to create, confine, understand, and control plasmas. ITER will provide a critical test of these technologies at power-plant-scale. Research goals of ITER are to demonstrate the availability and integration of essential fusion technologies; test components for a future power plant; and test tritium breeding module concepts. These technologies are essential for ITER to achieve its scientific research and performance goals and for the development of fusion energy.

Real-time plasma control requires an integrated set of tools to provide for plasma heating, current drive, and fueling; for pumping systems for control of edge plasma conditions and particle exhaust; and for magnets that provide the forces for confining, shaping and controlling the ITER plasma. Materials and plasma chamber systems must also provide simultaneously for power extraction and tritium breeding. Meeting these simultaneous demands in the strong electromagnetic field, intense fusion environment, and complex plasma confinement configurations is a challenge that requires important advances in several scientific fields and engineering disciplines.

Continued research can build a basis for extended pulse or perhaps even true steady-state operation of ITER. Nominally ITER will operate in a 400-second pulsed mode with the plasma current sustained by induction from its large Ohmic heating transformer. But current research is pointing toward operating modes for ITER that could stretch the inductive pulse length to perhaps an hour. Beyond that, research on auxiliary current drive and high self-driven current fractions is promising for true steady state, with none of the current supplied by induction. Essentially all of ITER's systems are designed for steady-state heat removal, although external hardware upgrades may be required, and issues of materials integrity and tritium inventory may need to be addressed.

Heating and current drive systems – Continued development of plasma heating and current drive systems will be a decisive factor in how far ITER can progress in advanced, long-pulse or even steady-state burning plasma research. Auxiliary heating systems must heat the ITER plasma to the burning plasma condition. To sustain the burning plasma, the spatial distribution of electrical current in the plasma must be controlled by the various neutral-beam and radio-frequency auxiliary systems to enable the plasma to enter a state of high self-driven current. Continued research in current fusion facilities on the application of these current-drive techniques and research on their technical application on ITER in terms of coupling to the plasma, steady-state cooling of components, insulators in the neutron environment, and applicable radio-frequency sources is needed.

Goal on ITER:	***Use RF systems to control ITER plasmas***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Develop RF sources and wave launchers***

Power exhaust – ITER will be the first experiment to produce copious fusion power (500 MW). The alpha particles deposit 100 MW of that power in the plasma. Up to possibly 100 MW of auxiliary power applied to heat the plasma and drive its currents will result in a total of 200 MW of thermal power that will be exhausted from the vacuum chamber with steady-state heat removal technology. No experiment to date has had to exhaust this much power. Thus ITER poses new challenges to develop applicable plasma operating modes in the plasma edge, which will require the development of erosion-resistant, plasma facing surfaces capable of handling high heat fluxes in a tritium environment (see Figure 2.1 goal on assessing plasma facing components).

Goal on ITER:	***Handle unprecedented power exhaust challenge***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Study first wall material options***

Particle fueling, exhaust, and tritium handling – Continued research is needed on alternatives to gas injection for fueling the plasma. (see Figure 2.1 goal on central fueling) due to the short gas penetration length. The exhaust stream primarily involves deuterium and tritium as only a small amount of the fuel is burned in the plasma in one circulation pass. In addition the stream consists of impurities, and helium, the thermalized alpha particles that are a product of the fusion reaction. All these constituents must be separated in the exhaust stream. Tritium must be carefully accounted for in all parts of the recirculation system. Of particular concern is tritium retention in the vacuum vessel by co-deposition with eroded first wall and divertor materials. In addition, the erosion of various types of plasma facing surfaces, the resulting transport of the eroded material into the plasma, and their eventual redeposition must be studied to make the best selection of wall-facing material.

Goal on ITER:	***Operate with sufficiently low tritium inventory***
	Provide central fueling in ITER
ITER Time Frame:	***High Gain DT Phase***
Preparatory Research:	***Study first wall material options***
	Develop tritium handling systems and advanced fueling for ITER

Superconducting magnets – ITER's ability to study long burning plasma time scales is enabled primarily by advances in superconducting magnet technology (see Figure 2.1 goal to learn from ITER magnet experience) The construction of ITER's superconducting magnets will be the largest system ever assembled, comparable to power-plant scale, and this construction must be supported with continued R&D on strand types, conductor assembly, and full magnet systems.

Goal on ITER:	***Assess the performance of power-plant scale magnets***
ITER Time Frame:	***Commissioning Phase***
Preparatory Research:	***Support superconducting magnet construction***

Neutron effects and blankets – The fusion neutrons will carry 400 MW out through the first wall into the shield assembly and the test blanket modules. How the fusion neutrons and their energy become distributed will be an important element of science on ITER. Neutron effects on components of plasma measurement and control systems will be a primary consideration. Test blanket modules will be fielded on ITER to learn how to capture the energy of the neutrons and breed tritium from lithium using these neutrons. The blanket module tests will become increasingly valuable as the pulse length of ITER increases at high fusion power (see Figure 2.1 goal on test blanket program).

Goals on ITER:	***Deploy, operate, and study test blanket modules***
	Operate very long pulses for blanket tests
ITER Time Frame:	***High Gain DT Phase to Fusion Technology Tests Phase***
Preparatory Research:	***Participate in a test blanket module program***

Measurement Systems for Burning Plasma Research – ITER must be an outstanding scientific research instrument. The quality and completeness of its plasma measurement and control systems will be a determining factor in the quality of its research output. A very extensive plan of plasma measurement systems has been prepared. Various systems have been distributed among the ITER partners. The United States will fulfill its commitments to provide its assigned measurement systems within the scope of the ITER project.

The U.S. fusion research program must support the development of new measurements and adaptation of known measurement techniques to enrich the research program on ITER. The plasma measurement systems on a research instrument as important as ITER will continuously evolve and improve, despite the new challenges of undertaking plasma measurements in a neutron environment.

Two areas of particular need are plasma turbulence and energetic particle measurements. As discussed above, ITER will explore plasma turbulence in a regime not accessible by any other experiment. Consequently there is an obligation to do a sufficient job of studying turbulence and confinement in this regime. The creation of an energetic alpha particle population from the plasma's own fusion reactions to self-heat the plasma is almost the simplest statement of what it means to realize a burning plasma. It is vital that detailed measurements of the alpha particle population be made, and yet these measurements are among the most difficult identified in the ITER plan.

Goal on ITER:	***Deploy turbulence and alpha particle measurements***
ITER Time Frame:	***Commissioning Phase to High Gain DT Phase***
PreparatoryResearch:	***Develop turbulence diagnostics for ITER***
	Develop measurement techniques for alpha particles

III Methods to evaluate whether ITER is promoting progress toward making fusion a reliable and affordable source of power

III.A Introduction

ITER offers the opportunity to explore and develop a new area of plasma physics, the burning plasma regime, with parameters close to those anticipated in a fusion power plant. This will be a critical step in the understanding of fusion plasmas and in the development of the scientific and technological basis for reliable and affordable fusion energy produced by a magnetically confined plasma. ITER will also extend plasma support technologies (e.g., magnets, plasma heating) well beyond existing capabilities and provide opportunities to test fusion power technologies.

ITER contributions toward developing fusion energy can be measured by two classes of metrics: a) improved understanding of fusion plasmas leading to better predictive capabilities; and b) progress toward achieving the characteristics of a safe, reliable and affordable source of power. These two classes of metrics are described in this chapter. Overall, the most suitable method to assess ITER contributions will be periodic peer review and assessments.

III.B Characteristics of a Safe, Reliable, and Affordable Fusion Power Plant

The U.S. has carried out extensive studies [10,11,12] over the past decade to determine the important characteristics for a fusion power plant with attractive environmental and economic features. The ARIES Studies, in conjunction with external review committees that have included electric utilities and power producers, has identified the following top-level goals that were also endorsed in Snowmass 2002 Summer Study. These goals help set overarching directions for fusion research:

1) Safety and environmental goals: low-level waste and no evacuation
    a. Requires that the fusion core is constructed entirely of low-activation material;
    b. Requires an intense 14-MeV neutron source and development and testing of power technologies using low-activation material.
2) Operational goals: High capacity factor and ease of maintenance
    a. Requires early integration of physics and technology
    b. Requires development of fusion technologies in parallel with ITER.
3) Economic Goals: 0.7-1.5 times present costs of electricity

a. Requires advanced tokamak mode (steady-state) operation;
b. Requires advanced technologies, in particular, high-efficiency blankets.

These goals have led to the development of a U.S. vision for a tokamak-based fusion power plant [10,11]. This vision defines the characteristics for a fusion power system, and provides a set of performance metrics that can be used to assess progress toward the fusion goal. A set of representative characteristics of a fusion DEMO based on the advanced tokamak (ARIES-RS/AT) is shown in Table 3-1. These can be used as performance metrics to measure ITER's contribution to fusion development.

The European and Japanese studies of concepts for fusion power plants have identified similar goals and technical characteristics, although the definition of DEMO and the planned development paths beyond ITER are somewhat different. [12]

III.C Progress on Understanding Critical Science and Technology Issues for Fusion Power

The U.S. science campaigns for ITER are described in Chapter II and summarized in Figure 2-1. The experimental schedule is laid out to first demonstrate physics understanding and technology capability during a weakly-burning/low-activation phase. When the understanding of plasma behavior and device capabilities is adequate, tritium will be introduced for burning plasma experiments in the "baseline scenario". Once these are satisfactorily completed, research into advanced operating regimes would begin. During these phases the technological capability of ITER would be increased to design parameters.

III.C.1 Scientific Understanding Areas of Interest to the U.S.

ITER will have the operational capability to carry out controlled burning plasma experiments, varying specific parameters to test physics understanding and technology performance. Some of the most important research areas (detailed in Chapter 2) include:

Research Areas	Long-Term Goals
• Non-linear coupling of alpha particle heating with transport and MHD stability	Understand, control and sustain high fusion gain burning plasmas
• Performance limiting macroscopic instabilities	Understand and stabilize pressure limiting instabilities to maximize fusion plasma performance
• Disruption avoidance and mitigation	Develop basic understanding of plasma disruptions leading to techniques for avoiding or mitigating the effects of disruptions

Research Areas	Long-Term Goals
• Confinement and thermalization of fusion alpha particles	Understand and control instabilities driven by alpha particles to improve alpha particle confinement and heating
• Energy and particle confinement in a burning plasma	Understand transport in the burning plasma regime, and develop predictive capability for confinement in base operating modes and advanced modes.
• Power and particle exhaust, including wall interactions and tritium retention	Understand edge plasma behavior and develop operating modes consistent with high-power, steady-state operation.
• Heating and plasma control through external energy, particle, and momentum sources	Develop predictive capability for use of external sources to control the plasma state and to achieve desirable operating modes.
• Neutron effects and tritium breeding	Deploy and study breeding blanket test modules to understand issues for DEMO.
• Measurement systems for burning plasma research	Develop and implement new diagnostics to enable detailed studies of burning plasma phenomena

A key element of the ITER research program is the creation of self-heated plasmas, optimized and integrated across all relevant scientific and technological areas. This is the mission that drives the ITER project and distinguishes it from previous experiments.

III.C.2 The Ultimate Test of Scientific Understanding – Predictive Capability

To carry out this mission (and prepare for projects that might follow), the program will need to demonstrate a deep understanding of the underlying scientific and technological issues. Ultimately, the test of this scientific understanding will be the ability to predict all significant aspects of ITER discharges, and the necessary characteristics of DEMO.

The ITER program will be organized around the production of integrated operational scenarios. To support the development of these scenarios and ensure safe and efficient operation, ITER discharges will be extensively modeled, at varying levels of sophistication, before they are run. To prepare for this, a major long-term effort has been proposed to develop self-consistent integrated simulations of the non-linear coupling in burning plasma discharges using high-performance computation. Two prototype components of this Fusion Simulation Project (FSP) have been initiated. As the FSP proceeds, validation by careful comparison with data from operating experiments will be required. As ITER research campaigns are carried out, physics understanding will be measured by the ability to predict discharge performance. The models will be continually updated to reflect new science learned on ITER and other (non-burning) devices. These tests for understanding will lead to a set of decision points during the ITER research program and will be carried out in a progression as ITER is brought to full performance. The success of the modeling can be evaluated quantitatively through formal validation protocols, but ultimately the breadth of physics understanding will be assessed through periodic review by scientific peers.

III.D Progress on Achieving the Plasma Performance Parameters Needed for Fusion

The key plasma performance parameters needed to achieve fusion power are shown in Table 3-1. These parameters provide an important yardstick for tracking progress in plasma performance toward fusion power. The first set of parameters on the physical size and strength of the magnetic field indicate that the ITER plasma is approximately as large as the plasma in a Demonstration (DEMO) of a fusion power plant. ITER is intentionally designed to be somewhat larger than a power plant DEMO plasma to provide a performance margin since some of the advanced science and technology features needed for a DEMO are not yet fully validated on existing facilities.

Table 3-1. Key Performance Parameters/Metrics for a Tokamak Fusion Plasma

		Metric		
Property	**Unit**	**To Date**	**ITER Goal**	**DEMO***
Major Radius	R (m)	3	6.2	5.5
Plasma Volume	V_p (m^3)	100	830	350
Magnetic Field (toroidal)	B_t (T)	11	5.3 (5.2)	6 - 8
Plasma Current	I_p (MA)	7	15 (9)	11
Fusion Power	P_f (MW)	16	500 (350)	2,000
Fusion Power Gain	Q	0.6	10 (5)	40
Plasma pressure	p (atm)	2	3 (2.5)	10
Fusion Power density	MWm^{-3}	0.3	0.5 (0.35)	6
Plasma Duration (P_{heat}>1 MW)	s	180	400 (3,000)	Steady-state
Self driven current fraction	f_{bs} , %	80	25 (50)	90
Plasma Exhaust/pulse	W (GJ)	1	60 (420)	Steady-state
Divertor Power Challenge	P_{heat}/R (MWm^{-1})	~10	~20	~100
Neutron Wall Loading	Γ_n (MWm^{-2})	0.1	0.5 (0.4)	4
Neutron Fluence	$MWam^{-2}$		0.3	30

Note:
Maximum parameters achieved To Date are not all simultaneous and not all on the same device
( ) in ITER Goal column indicates parameters for extended burn made possible with additional investment.
*DEMO based on an advanced tokamak as in U.S. ARIES-RS/AT power plant studies [10,11].

Fusion power, first produced by weakly burning DD plasmas and later with 50/50 DT plasmas, will be the most visible metric for tracking ITER performance until full fusion power is obtained routinely (~6 years). Fusion power gain (Q = Fusion-power-produced/input-plasma-heating-power) will be the key indicator of the quality of the fusion burn and a key metric for quantifying burning plasma capability. The ITER objective is Q ≥ 10 for conventional operation with 400s pulse duration, and Q ≥ 5 for advanced mode operation with 3000 s pulse duration.

The amount of fusion power produced by a given volume of plasma, fusion power density, is a metric related to the overall efficiency and cost of a fusion power system. A fusion power plant is expected to produce about 6 MWm^{-3}, which is 20,000 times larger than the fusion power density in the center of the sun. ITER's goal is to produce fusion power densities of 0.6 MWm^{-3} about 50% higher than present experiments and about 10% of a fusion power plant (DEMO). In the plasma temperature ranges of interest (10-20 keV), the fusion power density increases as $\sim p^2$ where p is the plasma pressure. ITER is expected to produce fusion plasma pressures of ~3 atmospheres (atm) compared to 10 atm needed for a fusion power plant.

The production of long duration burning plasmas is one of the unique features of ITER, far exceeding the capability of present day experiments. Progress in this critical area will be measured in terms of the pulse length(s) and by the production of fusion energy per pulse. Long pulses will be facilitated in ITER by utilizing the bootstrap or self-generated current. The fraction of the plasma current produced by the bootstrap current (f_{bs}) is a key metric for DEMO steady-state scenarios. In addition to the achievement of individual parameters beyond those of today's experiments, ITER will make a major contribution by achieving all these parameters simultaneously in an integrated manner.

During the preparation for and throughout ITER operation , several of the key parameters listed in Table 3-1 will be tracked by creating a chart of the parameter versus time. Some examples of expected plots would include:

- fusion power achieved versus calendar date,
- plasma duration versus calendar date
- fusion energy per pulse versus calendar date, and
- fusion gain versus calendar date.

These charts would be related to high level milestones for ITER, and the achievement of specific values and completion of specific experiments would trigger decision points for executing the next phase of the ITER Research Plan (Figure 2-1). See also Section III.F.

III.E Progress on Achieving the Plasma and Fusion Technology Capability Needed for Fusion

ITER will serve as a focus for the development of plasma and fusion technology for the next two decades, and has the goal to demonstrate the technological feasibility of fusion energy.

III.E.1 Plasma Technologies

A fusion power plant based on a tokamak will require the utilization of very large superconducting magnets. A defining feature of ITER is the implementation of the world's largest superconducting magnet at the scale of a fusion power plant. This magnet must operate very reliably at the design field of 5.3T in the fusion environment. These parameters will be close to those anticipated for a power plant and it is anticipated that experience on ITER and advances in superconducting cables over the next two decades will lead to more efficient superconducting magnets that would be utilized in DEMO.

Energetic neutral beams and high power radiofrequency waves will be employed on ITER to provide: plasma heating for initiation of the plasma burn, supplementary plasma heating and rotation drive during the burn, and plasma current drive to extend the plasma duration and enable access to advanced modes of operation. ITER plans to employ 33 MW of neutral beams derived from negative ions (NINB) with an energy of 1MeV. The NINB system will require additional development to achieve the power required for ITER. The ion cyclotron radiofrequency (ICRF) frequencies are in the range of broadcast TV and have a large experience base for the power sources. Electron cyclotron frequencies (ECRF) are in the microwave range and require the development of sources. The lower hybrid frequencies (LHF), under consideration for implementation to drive plasma current, are intermediate between ICRF and ECRF. The ICRF and LHF systems will require significant R&D to interface the RF launchers with the plasma. Development and testing of power plant compatible launchers will be an important research area.

Handling the plasma power exhaust is one of the great physics and technology challenges of fusion, and ITER will make major contributions in this area. The energy that must be handled per pulse is almost 500 times larger than present day experiments. The divertor power handling metric P_{heat}/R, increases significantly from today's experience to ITER with another large step from ITER to DEMO. Mitigation techniques using geometry modifications, and plasma radiation are being developed in present day tokamaks to reduce the power density on divertor plates, and these will be tested in the early phases of ITER operation. The DEMO will require even larger reduction in the fraction of the plasma exhaust power that reaches the divertor plates. First wall materials must also satisfy safety requirements for low long-term tritium retention. Even with success on ITER, there will be a large gap between those results and the capability required for the envisioned DEMO.

The key performance metrics for plasma technologies will be operation at design parameters (magnetic field, heating power, exhaust power, …), and the availability of the systems for the planned operational program.

III.E.2 Fusion Technologies

ITER will also carryout tests of blanket modules needed to breed the tritium to complete the DT fuel cycle and convert fusion power into electricity. Key fusion technology metrics are neutron wall loading (Γ_n = neutron power per wall area) and the total neutron fluence measured over the exposure of various samples and over the lifetime of ITER. ITER will provide data for neutron wall loading at about 15% of the values needed for a DEMO, which is useful for initial testing. The neutron wall fluence, which is important for materials damage, is planned to be $0.3 MWam^{-2}$, which is much less than the ~30 $MWam^{-2}$ needed for a DEMO.

An ongoing research effort on fusion technology and materials, in parallel with ITER, is required to develop the underlying science of fusion technologies. This effort would allow the U.S. to participate in the ITER blanket test program and provides the foundation to develop fusion technologies needed for DEMO and beyond.

ITER also represents a significant step forward from current experience in achieving the necessary level of overall system and component reliability required to reach ITER's goals of sustained operating time. Achieving such integrated operating experience is one of ITER's principle objectives and will be one of its most important accomplishments. ITER plant control and plasma control systems will need to be significantly more sophisticated than those of current experiments. While ITER will provide critical reliability data for some components, the required availability and system reliability for DEMO remains a large extrapolation beyond ITER.

III.F Milestones and Decision Points for U.S. Participation in ITER

A number of objectives and goals to be completed by 2015 are being discussed for the U.S. fusion research program in response to the Administration's Program Assessment Rating Tool (PART). The Long Term Performance Measures for magnetic fusion energy are:

- ***Predictive Capability for Burning Plasma:*** By 2015, demonstrate progress in developing a predictive capability for key aspects of burning plasmas using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects.

- ***Configuration Optimization:*** By 2015, demonstrate enhanced fundamental understanding of magnetic confinement and in improving the basis for future burning plasma experiments through research on magnetic confinement configuration optimization.

Each of these Long Term Performance Measures is supported by a series of short and intermediate term milestones. Several of these milestones are directly related to participation in ITER. An independent, expert panel will conduct a review and rate the program's progress toward achieving the long-term PART measures on a triennial basis.

As the ITER program is planned in more detail, it is foreseen that the participants in the international ITER Organization would determine a series of milestones and key decision points. The structure of the plan would follow the general form illustrated in Figure 1-1, and have many of the more detailed items illustrated in the U.S. research agenda for ITER (Figure 2-1). This time sequenced plan of ever increasing hardware capability has several phases of operation – each phase would have a set of science understanding milestones, and a set of plasma and hardware performance milestones that would feed into a decision point to move to the next operating phase. The U.S. might also choose to have additional milestones addressing items of interest to the U.S. Periodic peer reviews of ITER's progress in achieving the science understanding and performance milestones would be a key part of the U.S. assessment process.

III.G Evaluating the Effectiveness of U.S. Participation in ITER

ITER will be a major part of the U.S. fusion research program during the coming decades and it is essential that the U.S. be an effective participant. As the fusion program evolves to support ITER, a significant part of the U.S. fusion research program will be orientated toward supporting and enhancing U.S. participation in ITER. A series of goals should be established for the program to assess its success in supporting ITER. Some of these goals are defined in PART.

During the operational phase, the effectiveness of U.S. participation in ITER could be assessed by tracking the**:**

- Number of U.S. researchers and technologists participating in ITER,
- Number of experiments and technology tests proposed or led by U.S. participants,
- Achievement of scientific and technology milestones on ITER,
- Number of research and technology publications on ITER produced by U.S. participants,
- Citations of U.S. publications

The U.S. fusion program would benefit from periodic technical reviews and input from peers in the broader scientific and technology communities during the preparation for ITER as well as during ITER operation. As the energy goal becomes more dominant, the fusion community should also establish a working relationship with the environmental community to ensure that the vision for a fusion power plant has the desirable environmental features. Lastly, the fusion community should reestablish connections with the industrial community, which will ultimately be called upon to take over the development of fusion power. Examples would include:

- Scientific community review (e.g., fusion, FESAC, NRC, …)
- Environmental community advisory and review committee,
- Power producer advisory and review committee (e.g., EPRI, Utilities), and
- Industrial advisory and review committee

IV How Work on ITER Relates to Other Elements of the U.S. Fusion Program

IV.A Introduction

While ITER will take magnetic fusion deep into the burning plasma regime, it is clear that moving to a fusion power plant will require additional advances in plasma parameters and performance. Recognizing this, the NRC BPAC report, *Bringing a Star to Earth*, stated that "significant further developments will be required in order to develop an attractive fusion system." In particular, plasma pressure and energy confinement must be increased beyond the presently understood limits. Power requirements for plasma sustainment must be reduced, and the overall system must be simplified and made more reliable. The U.S. is addressing these broader goals with a science-based strategy that aims to broaden the understanding of fusion science and technology and thereby establish the knowledge base and predictive capability needed to decide on next steps beyond ITER.

The U.S. has planned its Science Campaigns to broaden the scientific foundations for fusion in the ITER era. Its goals are long-term, designed to provide the U.S. with the knowledge base for developing fusion energy. A portfolio of magnetic confinement experiments, spanning a range of configurations and sizes, supports the campaigns. Studying a spectrum of configurations, ranging from strongly externally controlled to self-organized (Figure 4.1), serves a dual purpose. First, it provides a range of variation in the plasma properties that enables understanding. Second, it provides solutions to practical fusion energy problems, such as control of high-pressure, well-confined plasmas; efficient sustainment; and power and particle exhaust. Focused technology efforts contribute to these solutions. The theory program, using analytic theory and a new generation of computer models and high-performance computers, develops predictive simulation tools and provides the necessary glue to tie research programs of differing configurations and sizes to each other and to ITER. The progress made between now and the time ITER operates will contribute to ITER by exploring regimes that help to optimize ITER operating scenarios and possibly exceed its base objectives. A new era will begin when ITER operates and begins to contribute to the Science Campaigns the necessary knowledge about the burning plasma regime.

As discussed in previous chapters, facilities in the U.S. will also have a continuing role in developing and testing solutions to issues encountered in ITER operation. This section gives an overview of the main components of the U.S. fusion research program outside those ITER participation activities.

The U.S. fusion research program is currently organized to be responsive to the strategy recommended by U.S. fusion scientists at their 2002 Snowmass workshop (Figure 4.2). Through participation in ITER, the U.S. will obtain the burning plasma knowledge that is needed, in combination with the magnetic configuration knowledge base from the U.S. portfolio described here, to establish a path to practical fusion energy beyond ITER. *Predictive understanding*, embodied in theory and simulation codes, is the key to making this possible.

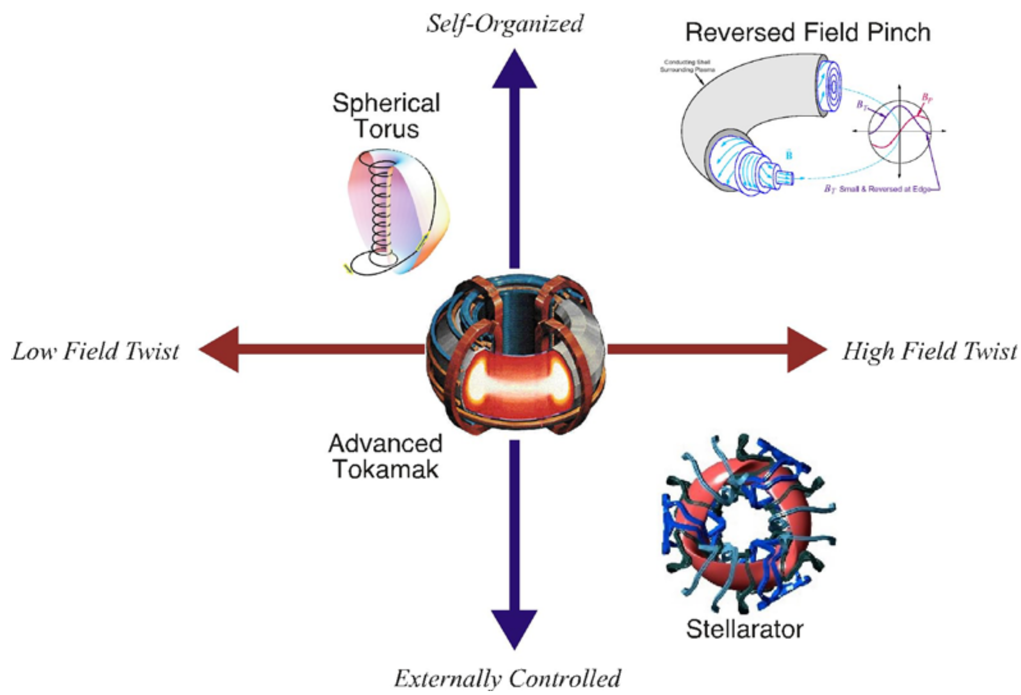

Figure 4.1. Major elements of the U.S. magnetic configuration portfolio, displayed according to their level of self-organization and the relative twist of their magnetic field lines, which is related to the stability of the configurations.

IV.B The Knowledge Base For an Attractive Power Plant

A program of innovation, configuration optimization, improved technology, and predictive simulation, supplementing ITER, ensures that the U.S. will have an adequate knowledge base for developing an attractive fusion power source beyond ITER.

IV.B.1 The Advanced Tokamak – Extending the tokamak

The advanced tokamak (AT) is a variant of the tokamak that has the aim of extending the performance of tokamaks beyond their currently understood limits and developing means to sustain tokamak plasmas for indefinite durations. The AT physics strategy takes advantage of self-generated plasma currents for sustainment, using active control of the internal plasma pressure and current distributions and special magnetic coils to maintain a stable configuration with good performance. Advanced tokamak plasma control is an active area for innovation, leading to gains in physics understanding, plasma control technology, and performance. Solutions developed on U.S. AT experiments could eventually be tested on ITER itself and lead to attractive fusion power plants based on the tokamak.

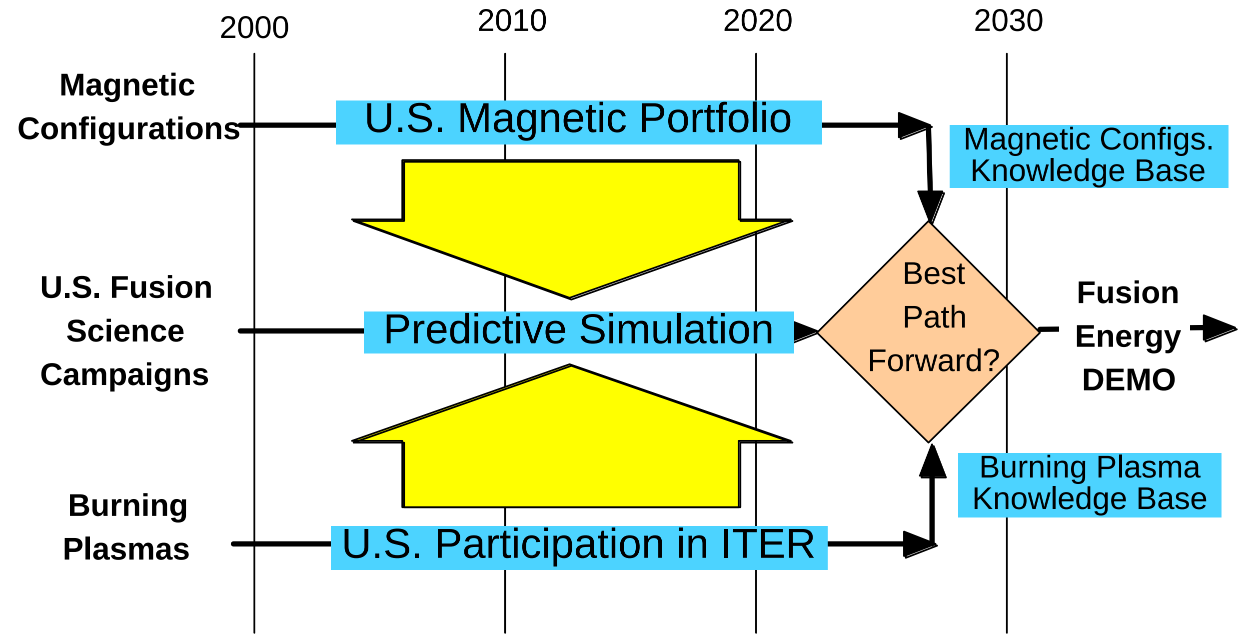

Figure 4.2. The U.S. Fusion Science campaigns will develop the predictive capability needed to choose the best path for fusion energy development beyond ITER. (Adapted from 2002 Fusion Snowmass report.)

IV.B.2 The Spherical Torus – Testing the Effects of Extreme Toroidicity.

The spherical torus (ST) configuration results when the aspect ratio of a tokamak is reduced by shrinking the hole in the center of the torus to its smallest possible size. The study of ST plasmas is of interest because it challenges tokamak-based physics understanding at the limits of toroidicity and shaping and hence provides an additional perspective on the scientific issues encountered in ITER. It provides access to stable high-pressure regimes, as well as unique conditions for studying the interactions between supra-Alfvénic energetic particles and the plasma that are relevant to fusion alpha particle behavior. A goal of ST research is to develop innovative start-up solutions that avoid the need for magnetic coils and other space-consuming components found in the center of tokamaks, and then be able to sustain the ST configuration with self-generated currents. A sustained ST configuration may form the basis for a relatively compact fusion system for component life testing that could proceed in parallel with ITER. It could thus support the development of fusion power plant technologies needed for the next step after ITER, providing a reduced-cost path to fusion energy development.

IV.B.3 The Reversed-Field Pinch – Exploring the Potential of Plasma Self-Organization

The reversed-field-pinch (RFP) is a toroidal configuration wherein the magnetic fields are generated mainly by internal plasma currents. These currents result in the magnetic field changing direction near the plasma edge region. It offers potential advantages, and provides a scientifically interesting contrast with configurations, such as the stellarator and tokamak, whose magnetic fields are generated mainly by coils. The RFP configuration results from internal processes (similar to those found in the natural plasmas such as the sun) that cause the plasma to seek a natural ("self-organized") state in which the plasma and magnetic pressures are in balance. Since those same processes can also increase the energy losses out of the plasma, an active research area is the study of innovative means of improving performance through plasma control. Efficient current sustainment techniques must also be developed. The RFP could lead to a power plant with attractive properties, arising from its low magnetic fields and high plasma pressure (relative to the magnetic pressure).

IV.B.4 The Compact Stellarator – Three-Dimensional Plasma with Magnetic Symmetry

The stellarator is a toroidal configuration in which the magnetic fields needed for plasma confinement and stability are generated by external coils with complex shapes. Such coils are able to satisfy the conditions for plasma confinement – twisted field lines and nested magnetic surfaces– without requiring externally driven plasma current. This allows very efficient steady-state operation and greatly reduced susceptibility to current-driven instabilities that can disrupt the plasma. Recent innovations have led to the design of stellarators with an underlying magnetic symmetry that are tokamak-like in the properties that are important for energy confinement and have lower aspect ratios (ratio of plasma radius to major radius) than earlier designs. The near-term U.S. focus is to test the predicted benefits of these compact stellarators including the benefits of three-dimensional shaping for a passively stable fusion plasma solution and its potential for tokamak-like enhanced confinement regimes. Its magnetic symmetry provides a high degree of physics overlap with tokamaks, so compact stellarator development can proceed based on the burning plasma knowledge gained from ITER. Through international collaboration, U.S. researchers will also participate in complementary stellarator research efforts in other countries and benefit from those substantial investments. As a potential post-ITER fusion development path the stellarator could be a simpler fusion system with reduced active plasma control requirements and improved reliability.

IV.B.5 Theoretical Fusion Science and Simulation.

The U.S program in fusion theory develops the basic concepts used to understand and discuss the behavior of fusion plasmas and mathematical formulations that allow quantitative prediction and comparison with experiment. Simulation brings together the mathematical equations of theory, mathematics and computer science techniques to solve the equations, and application of computers to numerically evaluate the solutions. There is a mutually supportive relationship between theory/simulation and experiments. Quantitative comparison between simulation and experimental results provides validation of the theories and simulations, while theory/simulation results provide understanding of the experimental measurements and contribute to improved device design and operation. The combination of U.S. theory/simulation/experiments support ITER by providing computational models valid in non-burning regimes, whereas ITER will extend validation of the models to burning plasma regimes. Validated burning plasma models can then be used to support concept innovation in advanced tokamaks, spherical tori, compact stellarators and reversed-field pinches.

IV.B.6 Emerging Concepts in Fusion Science and Technology.

The U.S. portfolio includes small-scale experiments that address unique fusion research issues to advance the understanding of plasma science and allow the study of speculative emerging concepts with potential for advanced fusion systems. These experiments and their associated theory efforts address basic configuration issues of formation, equilibrium, and stability. Emerging concepts explore engineering simplification (e.g., simpler plasma-wall interfaces) or more compact systems compatible with novel technologies (e.g. lithium metal walls). Among the concepts currently under study are spheromaks and field-reversed configurations, which, like the more developed RFP, rely on self-organization to establish conditions for confinement. The magnetic dipole is an example of a simple configuration similar to the magnetospheres of magnetized planets.

IV.B.7 Fusion Engineering Science – Tools for Controlling the Plasma

A broad U.S. engineering science program is focused on developing the plasma control technologies that enable confinement research facilities to meet their objectives. For example, the degree to which the hole in the bore of an ST can be shrunk depends on the use of wave launching structures to drive the plasma current during startup. Because of this there is a tight inter-relationship between the development of control technologies and the advancement of plasma physics understanding. Plasma control is important in varying degrees to the development of magnetic confinement configurations while the importance of fusion materials and chamber technologies is universal. Real-time plasma control requires an integrated set of tools to both monitor plasma parameters and respond as required with plasma heating, current drive, or fueling to manipulate plasma conditions. Plasma performance is sensitive to boundary conditions, so the plasma-facing structures and pumping systems are critical technologies for control of edge plasma conditions, as well as playing a role in heat and particle exhaust. All configurations depend on magnets for confining, shaping and controlling the plasmas and benefit from advances in magnet technology. The materials science component of this program is developing the knowledge base for high performance and environmentally attractive materials for the fusion environment. The chamber technologies program integrates materials science and other cross cutting disciplines such as safety, tritium handling, neutronics, and thermal-hydraulics into a program to develop advanced tritium breeding blankets for fusion systems. Through its contributions to ITER, the engineering science program will confront the requirements of a real burning-plasma environment for the first time, a stringent test that will benefit the development path for all magnetic fusion configurations.

EPAct Panel Charge

Department of Energy
Washington, DC 20585

February 16, 2006

Professor Raymond J. Fonck, Director
U.S. Burning Plasma Organization
Engineering Research Building
Room 341
University of Wisconsin
1500 Engineering Drive
Madison, Wisconsin 53706-1687

Dear Professor Fonck: Ray

As you are aware, the U.S. participation in ITER is supported strongly by the Congress with its language contained in the Energy Policy Act (EPAct) of July 27, 2005. The EPAct requires the Secretary of Energy to develop a Plan, in consultation with the Fusion Energy Sciences Advisory Committee (FESAC), for the participation of United States scientists in ITER that includes:

(i) The U.S. research agenda for ITER;
(ii) Methods to evaluate whether ITER is promoting progress toward making fusion a reliable and affordable source of power; and
(iii) Description of how work at ITER will relate to other elements of U.S. fusion program.

The EPAct also requires that the Secretary shall request a review of the plan by the National Academy of Sciences.

I would like the U.S. Burning Plasma Organization (USBPO) to develop this Plan in close cooperation with the U.S. fusion community. You have already engaged the community with the burning plasma issues through the USBPO workshop held at Oak Ridge on December 7-9, 2005. This workshop produced substantial information on the U.S. burning plasma activities since the Snowmass meetings about three years ago, and produced summaries of technical issues that the community identified for further research in support of ITER in the coming years. This wealth of information from the workshop should provide you the material to prepare the Plan required by the EPAct.

The Plan, including consultation with FESAC, has a due date in that the Plan must lie before Congress for 60 days before any long lead procurement funding can be expended. This, in coordination with the timing of the 120-day review by Congress of the international ITER Agreement, means that the development of the Plan, including the consultation with FESAC, must be completed by June 30, 2006.

I will inform FESAC at its meeting on February 28-March 1, 2006 that the BPO will prepare this Plan. Your status report on BPO to FESAC on March 1 should include your approach to prepare this Plan.

Please let me know any obstacles you see in completing this task by June 30, 2006. Please work with Erol Oktay in my office in carrying this work.

Sincerely,

Anne

N. Anne Davies
Associate Director
for Fusion Energy Sciences
Office of Science

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[11] F. Najmabadi and the ARIES Team, "Overview of the ARIES-RS Reversed-Shear Tokamak Power Plant Study," *Fusion Engineering and Design,* **38**, 3-25 (1997).

[12] For more information on ARIES Studies as well as links to similar studies in EU and Japan see http://aries.ucsd.edu/aries/