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Report
of the
Integrated Program Planning Activity
for the
DOE Fusion Energy Sciences Program

December 2000

U.S. Department of Energy
Office of Science

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(Report available at website: http://vlt.ucsd.edu/)

IPPA REPORT

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0.0 Executive Summary

Fusion is a scientific and technological grand challenge whose success depends on quality science conducted in a framework of a coherent Integrated Program Plan (IPP). In 1996, a strategic plan was developed for the restructured Fusion Energy Sciences Program with the overall mission to advance plasma science, fusion science and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.

The purposes of the IPP include:

1. *produce an integrated program plan for use by the DOE Office of Fusion Energy Sciences and the fusion community, including both MFE and IFE, and integrating experiments, theory, technology and basic plasma science.*

2. *provide the management of the fusion program at all levels, both at DOE and in the field, with improved mechanisms for accessing key technical and management information, to achieve better communications and performance accountability across the program.*

3. *elucidate and display the inter-connectedness and inter-dependency (the critical "connective tissue") which exists among the diverse parts of the national fusion energy sciences program, and which is necessary for achieving the program goals.*

Much of the work needed to develop an Integrated Program Plan has been completed and forms the basis for this report. This includes the following:

- The Fusion Energy Sciences Advisory Committee's (FESAC) report on "Opportunities in the Fusion Energy Sciences Program", June 1999.

- The Fusion Energy Sciences Advisory Committee's report on "Priorities and Balance within the Fusion Energy Sciences Program", September 1999.

- The Final Report of the Secretary of Energy Advisory Board's (SEAB) Task Force on Fusion Energy, August 9, 1999, as transmitted to Secretary Richardson by Andrew Athy on September 30, 1999.

- The Interim Assessment of the National Research Council's Fusion Science Assessment Committee, August 31, 1999.

- The output of the Fusion Community's Fusion Summer Study of July 1999.

The Integrated Program Plan presented in this report consists of three levels of program planning:

Level 1 - A top-level strategic framework. (Section 2.0)

Level 2 - An integrated description of goals and objectives leading to an implementation plan with measures of progress. (Section 3.0)

Level 3 - A structure for detailed, integrated planning, utilizing a database which organizes information on near-term tasks following from Level 2. Milestones and performing institutions to support the implementation approaches are to be included. (Introduced and outlined in Section 4.0).

Planning activities as represented by this document are part of an ongoing process. The next step is for FESAC to review this draft report. After that review is completed, and taking into account continued interactions and feedback with the broader fusion community, this report will be completed and sent to DOE's Office of Fusion Energy Sciences (OFES). Efforts will continue into FY2001 to implement the Level 3 database and, as experience is gained with that process, further improvements will be made. The information contained in Level 3 will be updated annually, whereas the information contained in Level 2 will be reviewed every two to three years and as part of a continuing assessment and update of the fusion program goals. Thus, this document is not static but will change in a dynamic fashion as the program evolves and responds to innovation and opportunities.

The central elements in this Integrated Program Plan are the four major Magnetic Fusion Energy (MFE) and two major Inertial Fusion Energy (IFE) program goals developed in the FESAC Priorities and Balance report:

MFE PROGRAM GOALS

1. *Advance the fundamental understanding of plasma, the fourth state of matter,* **,** *and enhance predictive capabilities, through the comparison of well-diagnosed experiments, theory and simulation.*

2. *Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.*

3. *Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements, and participate in a burning plasma experiment.*

4. *Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.*

IFE PROGRAM GOALS

1. *Advance the fundamental understanding and predictability of high energy density plasmas for IFE, leveraging from the ICF target physics work sponsored by the National Nuclear Security Agency's Office of Defense Programs.*

2. *Develop the science and technology of attractive rep-rated IFE power systems, leveraging from the work sponsored by the National Nuclear Security Agency's Office of Defense Programs.*

The main part of this report (Section 3.0) provides the Level 2 information for all these six goals in a common format:

- a statement of the FESAC goal followed by an explanatory description;
- a statement of its supporting objectives;
- an indication of how progress will be measured for each objective;
- a discussion of each objective including key issues; and
- a list and description of implementation approaches for each objective.

The Integrated Program Plan connects the goals, using the basic fusion program planning components (experiments, theory, and technology), to detailed fusion program activities and their objectives and milestones. Achievement of the goals of the program requires integration in at least six senses:

- integration of theory, experiment and technology;
- integration of the 4 MFE goals;
- integration between MFE concepts;
- coordination of OFES' IFE and National Nuclear Security Agency's Office of Defense Programs' Inertial Confinement Fusion (ICF) program and of the 2 IFE goals;
- integration of the MFE and IFE programs; and
- integration of the U.S. domestic fusion program and the world fusion program.

In its review of the program in 1999, SEAB stated, "Given constrained budgets, the wide variety of options, and the linkages of one issue to another, increasingly sophisticated management of the program will be required…(and) given the complex nature of the fusion effort, an integrated program planning process will be required." The charter from OFES for this activity requests that an Integrated Program Plan be prepared which includes the following information and capabilities:

- description of the program activities;
- intermediate milestones for each activity;
- interrelationships among the activities;
- linkages between program accomplishments and program goals;
- basis for performance-based management of the program;
- basis for resource planning; and
- basis for establishing accountability.

These SEAB and OFES requirements can be most readily accomplished by the creation and use of a research activities database and a concomitant database management system for the fusion program, which is described in general terms in Section 4.0.

1.0 Introduction and Background

The Integrated Program Planning Activity (IPPA) was commissioned in January of 2000 by Dr. N. Anne Davies (see Appendix I), Associate Director for Fusion Energy Sciences of DOE's Office of Science, to integrate a substantial amount of existing information "into a program plan that shows how the various elements of the program are interrelated and interdependent." This report has been prepared by the IPPA in response to the charter contained in Appendix I.

Much of the work needed to develop an integrated plan has been completed and forms the basis for this report. This includes the following:

- The Fusion Energy Sciences Advisory Committee's report on "Opportunities in the Fusion Energy Sciences Program", June 1999.

- The Fusion Energy Sciences Advisory Committee's report on "Priorities and Balance within the Fusion Energy Sciences Program", September 1999.

- The Final Report of the Secretary of Energy Advisory Board's Task Force on Fusion Energy, August 9, 1999, as transmitted to Secretary Richardson by Andrew Athy on September 30, 1999.

- The Interim Assessment of the National Research Council's Fusion Science Assessment Committee, August 31, 1999.

- The output of the Fusion Community's Fusion Summer Study of July 1999.

The overall IPPA goal is to develop an integrated plan with the following features:

- A description of the program that acknowledges both the science and energy goals of the program.
- A description of program activities needed to achieve the goals.
- A set of intermediate milestones for each program activity.
- A description of the interrelationships among the activities.
- A linkage between program accomplishments and program goals.

The formative discussions on the IPPA developed the concept of three levels of program planning information:

Level 1 - A top-level strategic framework.

Level 2 - An integrated description of goals and objectives leading to an implementation plan with measures of progress.

Level 3 - A structure for detailed, integrated planning, utilizing a database which organizes information on near-term tasks following from Level 2. Milestones and performing institutions to support the implementation approaches are to be included.

This report contains the Level 1 and 2 planning information. Level 1 is a review of previously issued strategic plans by DOE. The main part of this report is at Level 2 but the approach to establishing a Level 3 database is also described. The FESAC report on balance and priorities describes goals and 5, 10, 15-year objectives for the fusion energy sciences program. "Goals" refer to the principal technical thrusts of the program and "objectives" refer to steps toward meeting these goals. The Level 2 planning information in this report emphasizes the five-year objectives to respond to DOE's request for immediate milestones but includes, where appropriate, work related to longer-term objectives. The three levels then combine to form a comprehensive, Integrated Program Plan.

To implement the IPPA, Dr. Davies established a Steering Committee and Working Group whose membership is listed in Appendix II. The Steering Committee provides regular oversight to the Working Group which is responsible for preparing this report. A wide variety of methods were used to inform and interact with many segments of the fusion community in preparing this report. In carrying out the work of the IPPA, several important guidelines were implemented:

- Maintain key mission/goals/approach of restructured Fusion Energy Sciences Program
    - *strong science program with long-range energy applications*.

- Emphasize community involvement throughout the process by:
    - *general access websites.*
    - *numerous community networks.*
    - *Steering Committee.*
    - *FESAC review.*

- Make maximum use of approach/features/information of past year's reviews and activities.

- Make maximum use of existing infrastructure of program (committees, task forces, groups, etc.) to encourage community participation and support. Use information developed in the annual budget process.

- Develop and maintain effective liaison with DOE's Office of Fusion Energy Sciences staff.

- Be flexible and modify planning process to reflect input and suggestions.

The major elements of this report are as follows:

Section 2- description of the overall strategic framework and program integration/interconnections (Level 1).

Section 3- principal scientific program goals and objectives as developed by FESAC are expanded to include implementation approaches (Level 2).

Section 4- description of research (budget) categories and their relationship to goals and objectives and a framework for implementing a detailed database on tasks, milestones/metrics and performing institutions (Level 3).

2.0 Strategic Framework and Program Integration (Level 1)

The purpose of this section is to describe the strategic framework for the Integrated Program Plan (IPP), namely the top level (Level 1) assumptions upon which the IPP is constructed. This section provides a brief overview of the key program and policy doctrines that form the foundations of the IPP, and then describes program integration and interconnections from several perspectives.

The Fusion Energy Sciences Advisory Committee (FESAC), the official advisory body to the USDOE on fusion energy matters, recently characterized the fusion program as follows[1]:

> "Fusion is a scientific and technological grand challenge. It has required the development of the entire field of high-temperature plasma physics, a field of science that contributes to the description of some 99% of the visible universe. Plasma physics also provides cross-cutting insights to related fields such as nonlinear mechanics, atomic physics, and fluid turbulence. Quality science has always been the key to optimizing fusion systems. Throughout the history of fusion energy research, the combination of exciting, challenging science and the lofty energy goal has attracted gifted young people into fusion research, many of whom have gone on to make important contributions in related scientific fields and in the commercial technology arena…
>
> "Recent years have brought dramatic advances in the scientific understanding of fusion plasmas and in the generation of fusion power in the laboratory. Today, there is little doubt that fusion energy production is feasible. The challenge is to make fusion energy practical. As a result of the advances of the last few years, there are now exciting opportunities to optimize fusion systems so that an attractive new energy source will be available when it may be needed in the middle of the century. The risk of conflicts arising from energy shortages and supply cutoffs, as well as the risk of severe environmental impacts from existing methods of energy production, are among the reasons to pursue these opportunities…
>
> "The DOE Fusion Energy Sciences Program is exploring multiple paths for optimizing fusion systems, taking advantage of both the strong international program in magnetic fusion energy and the strong DOE Defense Program's effort in inertial confinement fusion. As in other fields, the advancement of plasma science and technology requires facilities in a range of sizes, from the largest devices that press the frontier of high-temperature plasmas to smaller experiments suitable to begin the exploration of innovative ideas for fusion optimization. The very largest facilities may require international collaboration, while the smallest are natural for university-scale investigation. Specific questions of plasma science and fusion technology set both the required number and the required scale of the experimental facilities in the program."
>
> "The large international magnetic fusion program, at over a billion dollars per year, is an indication of the world-wide commitment to the development of a practical magnetic fusion power system. This global investment also provides dramatic leverage for U.S. research."

The Fusion Energy Sciences program is a part of the Department of Energy's Science program. The mission of the Office of Science is[2]:

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[1] FESAC Report, "Opportunities in the Fusion Energy Sciences Program," June 1999

[2] USDOE, Draft "Strategic Plan for the U.S. Fusion Energy Sciences Program," May 2000

> *To advance basic research and the instruments of science that are the foundations for DOE's applied missions, a base for U.S. technology innovation, and a source of remarkable insights into our physical and biological world and the nature of matter and energy.*

The five central goals for the Office of Science are:

- *Fuel the future--Science for clean and affordable energy.*
- *Protect our living planet--Energy impacts on people and the biosphere.*
- *Explore matter and energy--Building blocks from atoms to life.*
- *Provide extraordinary tools for extraordinary science--National assets for multidisciplinary research.*
- *Manage as stewards of the public trust--Scientific and operational excellence.*

Fusion research directly supports these Office of Science goals because it offers the prospect of an abundant and clean source of energy while developing and nurturing the science of plasmas, the fourth state of matter. Plasmas represent a complex set of phenomena, coupling particles and electromagnetic fields, which stimulate and make use of detailed experiments, innovative diagnostics, and advanced computational methods. The Fusion Program also contributes substantially to a broad range of basic and engineering sciences and operates several national research facilities.

The Fusion Energy Sciences Program mission statement and policy goals, as stated below, were adopted by the US DOE based on the recommendations for a restructured fusion energy sciences program submitted by the Fusion Energy Advisory Committee in 1996.[3] The thrust of the new strategy is to emphasize advancing the science and technology knowledge base, including basic plasma science, needed for an economically and environmentally attractive energy source. Scientific advances underlie this program strategy. The new approach is, in essence, a science-based strategy for the development of fusion energy.[4]

MISSION
Advance plasma science, fusion science, and fusion technology – the knowledge base needed for an economically and environmentally attractive fusion energy source.

POLICY GOALS
1. *Advance plasma science in pursuit of national science and technology goals.*
2. *Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program.*
3. *Pursue fusion energy science and technology as a partner in the international effort.*

In the 1999 Opportunities Document, FESAC stated[1]: “The fusion energy quest *demands* excellent science—it will fail without the nourishment of scientific advance and deep scientific understanding. At the same time, the fusion program has an extraordinary record in *generating* excellent science—bringing crucial insights as well as conceptual innovations to such disciplines as fluid mechanics, astrophysics, and nonlinear dynamics. Most of the scientific advances engendered by fusion research have begun as discoveries about the behavior of that most complex state of matter, plasma.”

The quest for fusion energy has driven intensive research in basic plasma physics, leading to a number of discoveries of fundamental importance to such disciplines as kinetic theory, transport theory and nonlinear dynamics. Some key questions (see Appendix III) being pursued in the fusion program are:

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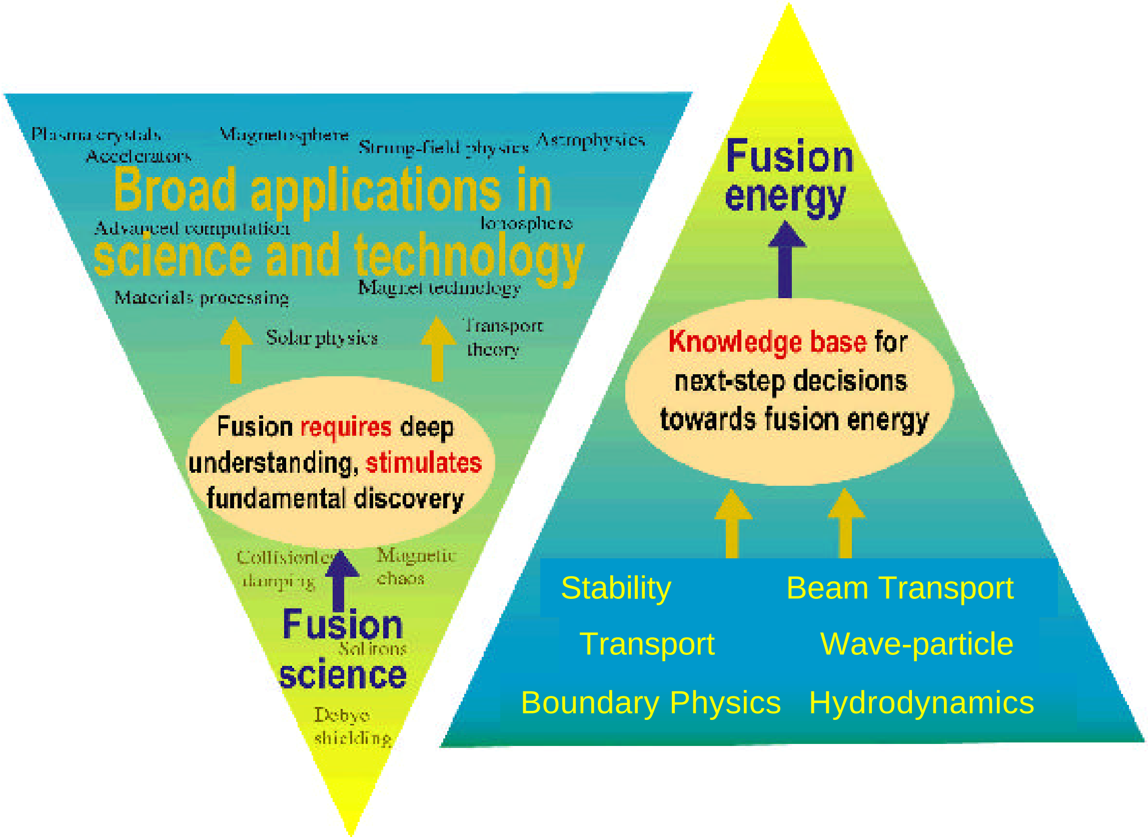
[3] FEAC Report, “A Restructured Fusion Energy Sciences Program,” Jan. 27, 1996

[4] Report DOE/ER-6084, “Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program”, Aug. 1996

- *What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled?*
- *What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems?*
- *What are the fundamental causes and nonlinear consequences of wave interactions with thermal and non-thermal particles?*
- *What are the fundamental processes occurring near the boundary of a confined plasma and how can the interaction between the plasma and material surfaces be controlled?*
- *How do limits on driver intensity and target requirements for irradiation symmetry, hydrodynamic instability, pulse shaping, and fusion ignition impact the gain achievable in inertial fusion targets?*
- *What are the limits to charged particle beam transport and focal intensities in the beam current regimes of interest to IFE?*
- *What are the most effective means to address the technological needs of present fusion research activities as well as future fusion reactors?*

This knowledge base has not only served fusion, but nurtured scientific advances in many other areas of science and technology. These themes are highlighted in Figure 2.1.

Figure 2.1 The quest for fusion energy has driven intensive research in basic plasma physics, leading to discoveries of fundamental importance.



PROGRAM DIRECTIONS AND BALANCE

The program directions and balance contained in this report reflect the recommendations of FESAC as described in the "Report of the Panel of Priorities and Balance."[4]. This report responded in part to a charge issued on October 9, 1998, by Dr. Martha Krebs to lead a community assessment of the restructured U.S. program. FESAC and its panels undertook a year-long process to identify the opportunities and requirements of a fusion energy science program; to identify goals, metrics and decision criteria; to consider issues of program balance; and to make recommendations on program content, emphasis and balance. Its underpinnings followed from recent reviews of the U.S. fusion program. It was prepared by members of FESAC, using input from a sequence of three FESAC panels, a summer meeting of representatives of the entire fusion community, presentations on the entire fusion program made during visits of fusion sites, and from SEAB and NRC panels.

In addressing the relative balance and priorities, the FESAC response reaffirmed "the national custodial responsibility of OFES for the health and vitality of the discipline of plasma science." With regard to fusion, the Panel endorsed and took as a starting point the Final Report of the SEAB Task Force on Fusion Energy, *Realizing the Promise of Fusion Energy,* which stated: "In light of the promise of fusion and the risks arising from increasing worldwide energy demand and from eventually declining fossil energy supply, it is our view that we should pursue fusion energy aggressively."

The FESAC Panel identified the achievement of a more integrated national program in MFE and IFE as a major programmatic and policy goal in the years ahead. Two areas of research common to both MFE and IFE deserve special encouragement in this regard: theory and selected areas of chamber technology. Establishing an optimal balance between IFE and MFE in a more integrated national program in fusion energy sciences should be based on the following guiding principles:

- *The MFE and IFE programs should be consistent with their respective time frames, set in part by:*
  - *MFE opportunities to participate in major international experiments.*
  - *IFE opportunities to leverage the National Nuclear Security Agency's Office of Defense Program funded Inertial Confinement Fusion (ICF) program.*
- *Specific elements of science and technology critical for evaluating the ultimate energy potential of IFE and MFE, such as interaction of the plasma with chamber walls, should be brought to comparable levels of maturity.*
- *The dramatic advances in the predictive power of modern theory and simulation make these tools essential elements of a cost-effective program.*
- *A common peer-review process for MFE, IFE, and cross-cutting activities should be implemented wherever possible.*
- *Cross-cutting science and technology, with application to both MFE and IFE, deserves special encouragement.*
- *Attracting and retaining creative young scientists in the combined program.*

The MFE research plan is motivated by three considerations central to the restructured fusion energy sciences program: the continued development of fundamental scientific understanding and innovative technologies, the advancement of innovative magnetic concepts, and the time frame of

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[4] FESAC Report, "Priorities and Balance Within the Fusion Energy Sciences Program," Sept. 1999

the international fusion effort. In the five-year time frame, the international fusion community will be making construction decisions for major next-step experiments. The MFE plan assures that the U.S. remains actively engaged with the international community and is able to participate in a meaningful way with the worldwide development of magnetic fusion energy. Also on approximately a five-year time scale, our understanding of some of the new magnetic fusion concepts can be sufficiently advanced to warrant consideration for study at the larger scales which more closely resemble fusion conditions.

The near-term IFE research plan is motivated by the goal of initiating an Integrated Research Experiment (IRE) program to complement results expected to be obtained on NIF and other Defense Programs and international single shot target physics facilities. One essential feature of the IFE program is an increased emphasis on chamber technology, including beam propagation. The IFE plan aims at obtaining the scientific information and technology development needed to make an IRE decision in roughly the five-year time frame, permitting an effective interaction and leverage between a balanced IFE research program and the NIF and other inertial fusion programs in target physics.

The central elements of these plans are represented by four MFE and two IFE programmatic goals. These goals are:

MFE PROGRAM GOALS

1. *Advance the fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through the comparison of well-diagnosed experiments, theory and simulation.*

2. *Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.*

3. *Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements, and participate in a burning plasma experiment.*

4. *Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.*

IFE PROGRAM GOALS

1. *Advance the fundamental understanding and predictability of high energy density plasmas for IFE, leveraging from the ICF target physics work sponsored by the National Nuclear Security Agency's Office of Defense Programs.*

2. *Develop the science and technology of attractive rep-rated IFE power systems, again leveraging from the work sponsored by DOE in the DP ICF Program.*

The knowledge base for next step decisions in the development of fusion energy will be based upon these six key program goals. These goals are the guiding basis for the Integrated Program Plan.

Although the six fusion energy science goals are listed separately for MFE and for IFE, when taken together, they represent major steps toward the world's ultimate goal for fusion research: the ability to proceed to the development of a practical energy source. As described by FESAC in their report *Opportunities in the Fusion Energy Sciences Program*,[1] the U.S. fusion community has created a programmatic structure that includes both MFE and IFE approaches within a unified framework. This framework defines "stages of development" that are followed during the scientific investigation and technical development of possible approaches to a fusion energy source. (See Figure 2.2). The framework's central focus is to provide a logic that makes each stage practical and affordable while optimizing the scientific and technological research addressed at each stage. There are currently various concepts at the first three stages of development listed below. New concepts enter at the concept exploration level.

The five developmental stages of development are defined in the FESAC document:

Concept Exploration is typically at <$5M/year and involves the investigation of basic characteristics. “Concepts” should be interpreted to include experiments designed to test important basic fusion-relevant science “concepts” as well as potential reactor “concepts”. Experiments cover a smaller range of plasma parameters (e.g., at <1 keV) and have fewer controls and diagnostics than a PoP level experiment. However, sufficient diagnostics are required to carry out high quality, scientific investigations.

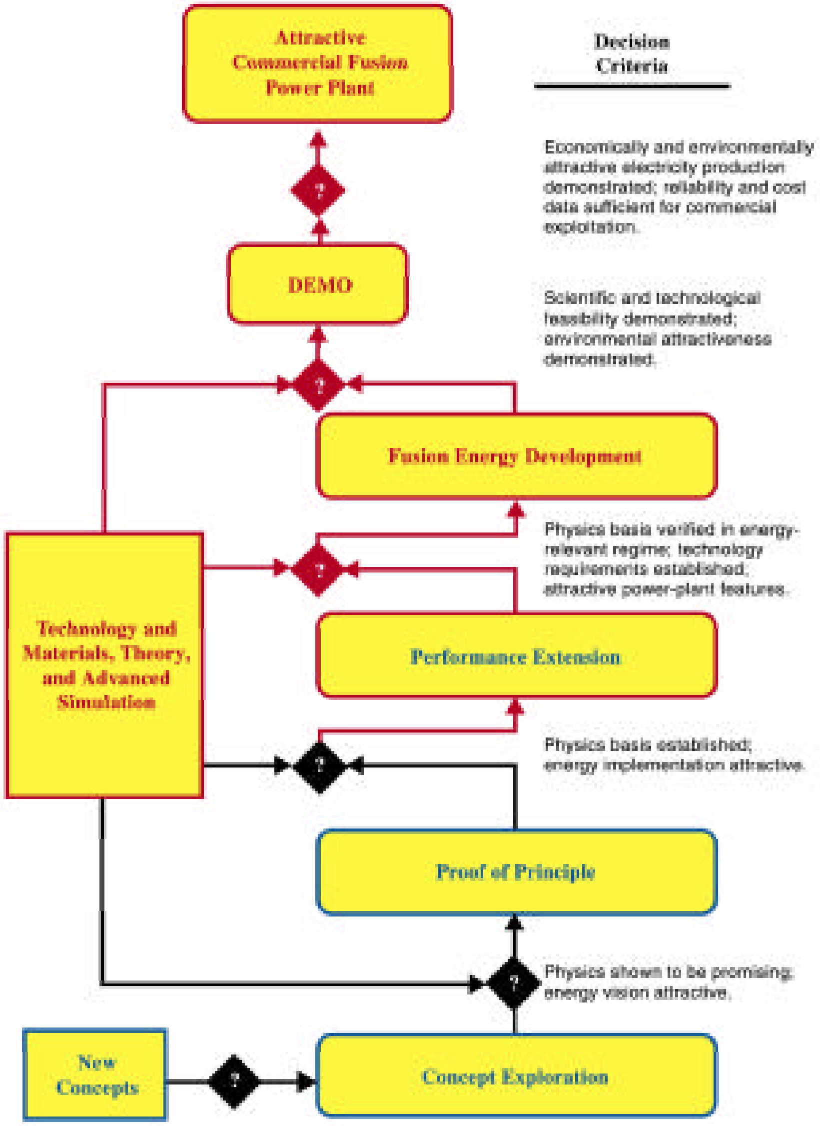
Proof-of-Principle (PoP) is the lowest cost program ($5M to $30M/year) to develop an integrated understanding of the basic science of a concept. Well-diagnosed and controlled experiments are large enough to cover a fairly wide range of plasma parameters, with temperatures of a few kiloelectron volts, and some dimensionless parameters in the power plant range.

Performance Extension programs explore the physics of the concept at or near fusion-relevant regimes. Experiments have a very large range of parameters and temperatures >5 keV, with most dimensionless parameters in the power plant range. Diagnostics and controls are extensive.

Fusion Energy Development program develops the technical basis for advancing the concept to the power plant level in the full fusion environment. It includes ignition devices, integrated fusion test systems, and neutron sources.

Demonstration Power Plant is constructed and operated to convince electric power producers, industry, and the public that fusion is ready for commercialization.

Figure 2.2 Logic Framework for Stages of Fusion Energy Development. The integrated plan refers to this structure in characterizing the activities and goals.



INTEGRATED PROGRAM PLAN (IPP)

Starting with the six FESAC programmatic goals stated above as “givens”, this Integrated Program Plan connects the goals, using the basic fusion program planning components (experiments, theory, and technology), to the detailed fusion program activities, and their objectives and milestones, both near term and longer term, including basic science research in each component area. The purposes of the IPP include:

1. *produce an integrated program plan for use by the DOE Office of Fusion Energy Sciences and the fusion community, including both MFE and IFE, and integrating experiments, theory, technology and basic plasma science.*

2. *provide the management of the fusion program at all levels, both at DOE and in the field, with improved mechanisms for accessing key technical and management information, to achieve better communications and performance accountability across the program.*

3. *elucidate and display the inter-connectedness and inter-dependency (the critical "connective tissue") which exists among the diverse parts of the national fusion energy sciences program, and which is necessary for achieving the program goals.*

The national fusion program is a complex ensemble of program activities, involving many areas of science and technology, which connect to broader scientific programs outside of the fusion energy sciences program. One of the purposes of the IPP is to shed light on these scientific inter-relationships. The connectivity and integration of the three program planning components (experiments, theory, and technology), together with their major technical and management interfaces, is discussed below.

PROGRAM INTEGRATION AND INTERCONNECTIONS

FESAC recognized a variety of forms of integration as key to the success of the U.S. fusion program. In fact, achievement of the goals of the restructured U.S. fusion program requires integration of the program in at least six senses:

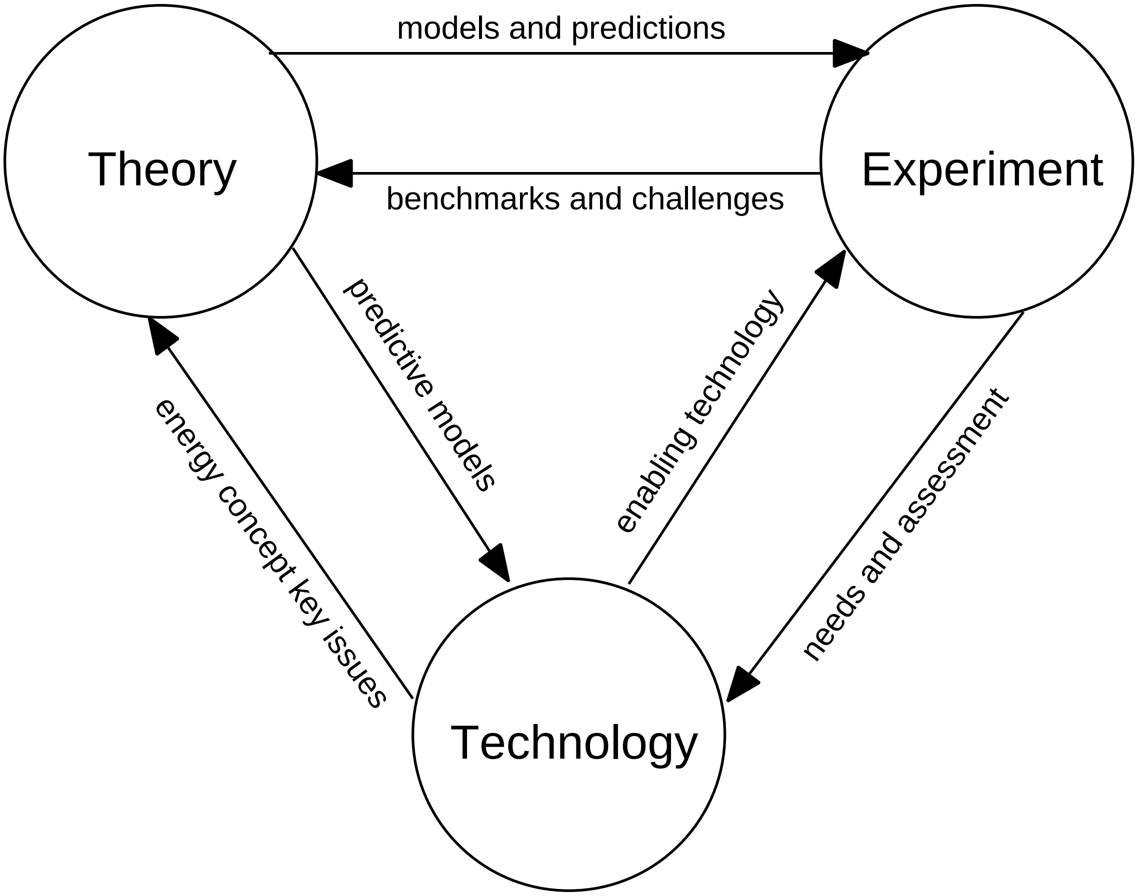
- integration of theory, experiment and technology;
- integration of the 4 MFE goals;
- integration between MFE concepts;
- coordination of OFES' IFE and National Nuclear Security Agency's Office of Defense Programs' ICF program and of the 2 IFE goals;
- integration of the MFE and IFE programs; and
- integration of the U.S. domestic fusion program and the world fusion program.

This section addresses these six integration perspectives.

Integration of Theory, Experiment and Technology

The fusion program is fundamentally multi-disciplinary and innovative which drives the strong coupling between the three major areas of theory, experiment and technology, as illustrated below.

Figure 2.3 Interconnections of Theory, Experiment and Technology.



Consistent with its nature as a science program, strong interactions between experiments and theory provide insights that enable the improvement of understanding; theory and simulation develop physical models and predict the outcomes of experiments; the experiments provide benchmarks of the theories - sometimes confirming predictions but often challenging the theorists to improve the models. Detailed diagnostic measurements of the plasma profiles and of plasma fluctuations are key to understanding plasma behavior. The experimental facilities frequently confront the technological state-of-the-art and are enabled by developments in the technology program; conversely, the experiments utilize the technologies, assess the performance of the technologies, and identify needs for further development. Theory provides predictive models which are used by the systems analysts in the technology program both to design new facilities and to optimize the vision of alternative fusion reactors; conversely, the technology program identifies directions where improved understanding of the plasma behavior would significantly improve reactor visions.

FESAC explicitly recognized the role of the technology program in enabling the experimental program by recommending to “revitalize the technology program to provide for continued innovation in this area because of its overall importance to the success of fusion science and fusion energy and applications [and to] utilize systems studies to identify attractive fusion energy concepts and affordable development paths.”

FESAC recognized that the expected increase of understanding motivates a five-year decision-point to consider advancing to the next level of integration: “Also on approximately a five-year time scale, our understanding of some of the new magnetic fusion concepts can be sufficiently advanced to warrant consideration for study at the larger scales which more closely resemble fusion conditions."

Integration of the 4 MFE Goals

The four FESAC goals together form the structure for a network of interconnections that enable the U.S. fusion program. As illustrated in Figure 2.4, the four goals are mutually supportive; each goal is associated with activities that both provide tools and capabilities to enable pursuit of the other goals and benefit from the outputs of the other goals' activities.

Advanced fundamental understanding of plasmas and enhanced predictive capabilities (Goal 1) are achieved by developing theoretical models, conducting general plasma science experiments, and analyzing data and incorporating understandings from innovative confinement concept devices (Goal 2) and from high-performance plasmas and low-gain burning plasmas (Goal 3); in return, the advanced understanding (Goal 1) contributes prediction methodologies and tools for design and data interpretation (Goal 2 and 3). Similarly, advanced understanding (Goal 1) provides improved predictive capabilities to systems analysts (Goal 4) who respond with visions for future directions. Studies of innovative magnetic confinement configurations (Goal 2) benefit from the plasma control tools and understanding developed by high-performance plasma studies (Goal 3), and provide conceptual innovations that can improve the high-performance plasma studies (Goal 3). The development of relevant technologies (Goal 4) enables both innovative (Goal 2) and high-performance (Goal 3) plasma studies by providing plasma control tools, plasma diagnostics, experiment design, and systems analyses; correspondingly, the experimental programs (Goal 2 and 3) identify technology needs, refine reactor visions, and provide experimental data and performance projections to provide a basis for designing and optimizing future facilities (Goal 4).

Integration Between MFE Concepts

The fusion program addresses the spectrum of scientific topics via research on a range of device configurations. Pursuit of understanding of the scientific topics (MHD, transport and turbulence, wave particle interactions, and plasma wall interaction) benefits from experiments and theory on devices that span the space of *externally controlled* to *self-organized,* as shown in Figure 2.5. Devices whose configurations are largely controlled by strong plasma currents are generally more susceptible to MHD modes and also offer opportunities for the study of MHD instabilities; control of MHD instabilities by profile control, feedback control, etc., on one configuration could provide key opportunities for MHD stabilization in other configurations; for example, work on the feedback stabilization of resistive walls modes on tokamaks is also key to progress in spherical tori (ST) and reversed field pinches. Understanding of transport and turbulence is aided by studies in the full range of configurations; understanding, suppression and control of turbulence and transport are key to optimization of all configurations. Externally controlled configurations, like advanced stellarators, tokamaks and ST's, utilize plasma-driven currents to reduce the need for externally-driven currents; understanding and control of those so-called "bootstrap currents" benefit the range of externally controlled configurations. In a complementary fashion, studies of helicity injection and tokamak current drive benefit the range of self-organized configurations. Power and particle control is a key issue for the full range of configurations; studies of the plasma wall interaction provide insights and direction for this control in the range of configurations.

Figure 2.4 Interconnections of the Four MFE Goals.

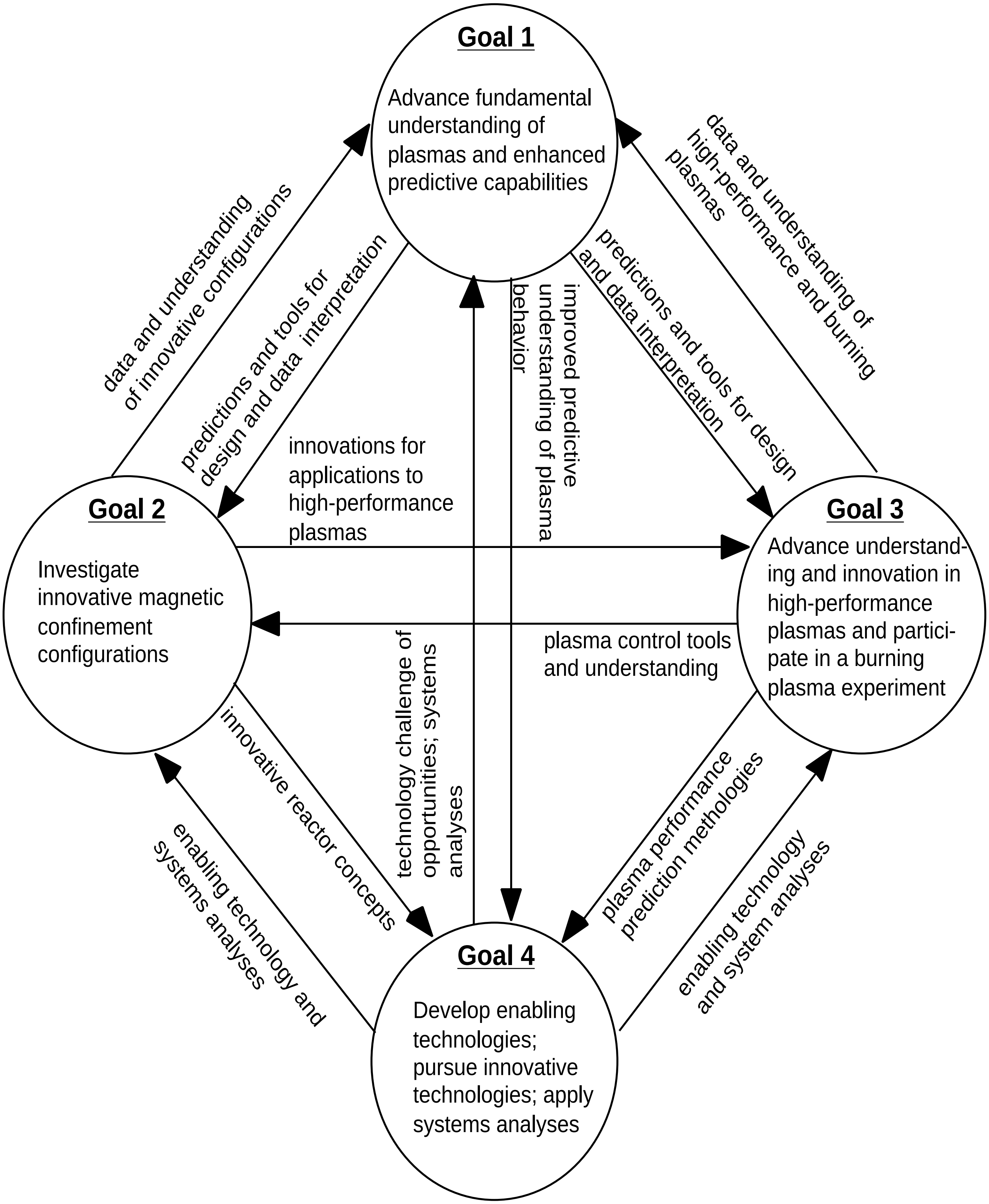
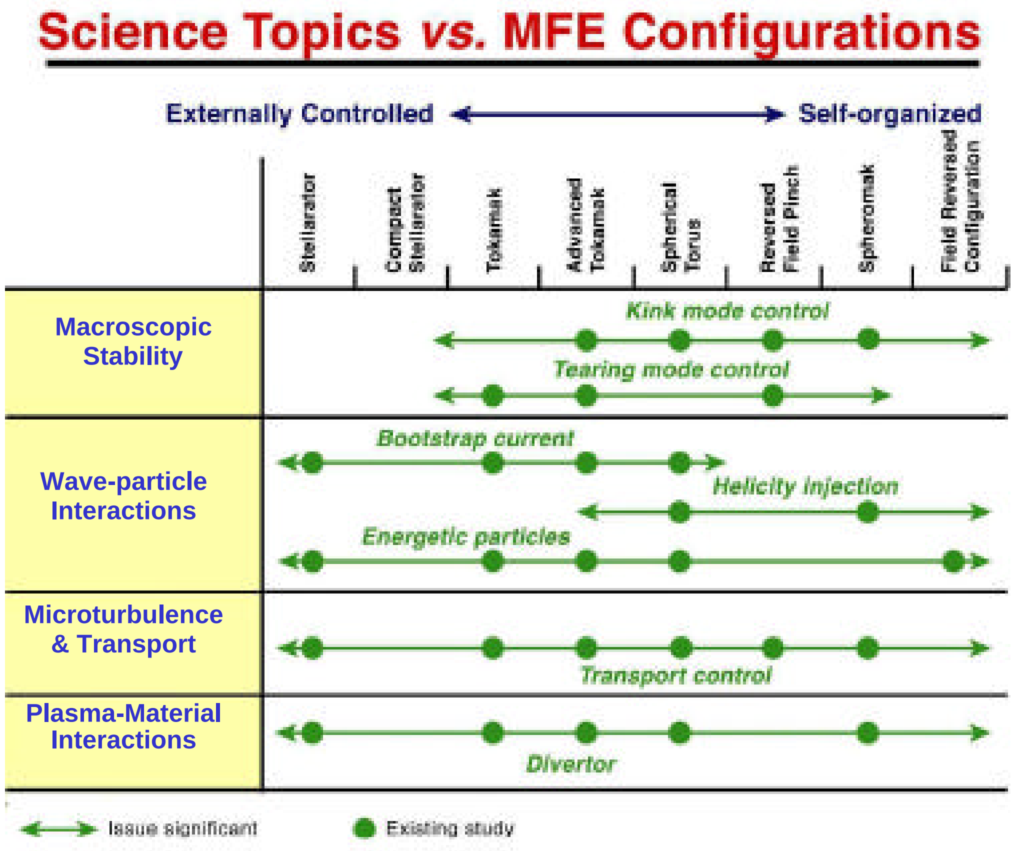


Figure 2.5 Scientific Integration Between MFE Concepts.



Coordination of OFES' IFE and National Nuclear Security Agency's Office of Defense Programs' ICF Program and of the Two IFE Goals

There is a high level of synergy between the Department of Energy's Office of Fusion Energy Sciences (OFES) IFE program addressing IFE-specific needs, and the National Nuclear Security Agency's Office of Defense Programs' (DP's) Inertial Confinement Fusion (ICF) target physics program. As written by FESAC:

> "The DP program addresses the critical target physics issues in single shot experiments. This allows a modest cost OFES program to focus on the development of high pulse-rate, efficient, reliable, and affordable drivers and associated fusion chambers, target fabrication, and target injection."

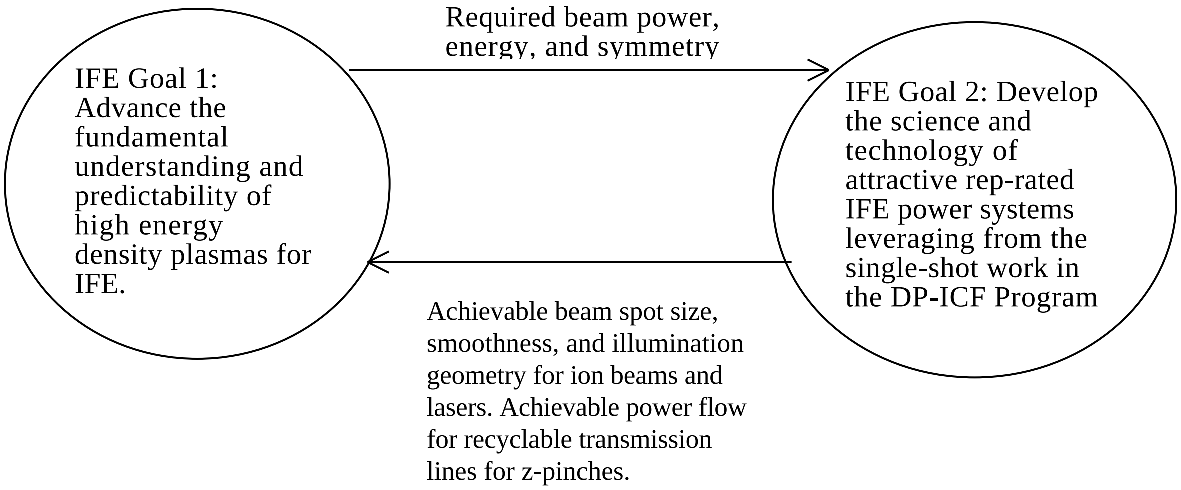
FESAC highlighted that the IFE program should be "consistent with IFE opportunities to leverage the DP funded ICF program: "The IFE program relies on the DP-funded ICF program for much understanding of target physics."

FESAC specifically called for coordination roles between the OFES IFE program and the defense and international programs: "These approaches leverage the National Nuclear Security Agency's Office of Defense Programs' large investments in laser and pulsed power facilities, target design capabilities, and experimental infrastructure including target fabrication and diagnostics. The heavy ion driver approach leverages the large worldwide program in accelerator development."

The role of information from NIF and other elements of the ICF Program in a decision to construct an IRE will be reviewed when updates to the schedule for NIF construction and operation, as well as the general ICF Program plan, become available.

SEAB called for dual-purpose work between IFE and ICF: "DP should dedicate funds to dual-purpose activities, consistent with DP's mission statement, that exploit the synergy between the defense work and IFE science. For example, DP might appropriately take the lead in the development of high-average-power lasers because of DP's very significant involvement and accomplishments in the laser field."

Figure 2.6 Interconnections of the Two IFE Goals.



IFE Goals 1 and 2, dealing with target physics, chamber technology, and repetition-rated drivers, must be integrated because of the need for compatibility between drivers and targets. (See Figure 2.6). Implosion experiments and computer models are conducted within the National Nuclear Security Agency's Office of Defense Programs in Inertial Confinement Fusion. However, the requirements for higher target gain at repetition rates for inertial fusion energy demand unique target design features and extensions of computer models to satisfy repetition-rated chamber, driver, and target fabrication constraints. The target design and chamber design depend on the characteristics of the driver. Thus, development of satisfactory repetition-rated IFE drivers and targets requires tight integration with IFE-specific target design.

Integration of the MFE and IFE Programs

In its report on Priorities and Balance, FESAC called for "the achievement of a more integrated national program in MFE and IFE as a major programmatic and policy goal in the years ahead."

FESAC emphasized that "Cross-cutting science and technology, with application to both MFE and IFE, deserves special encouragement." The magnetic fusion and inertial fusion programs share several areas where joint studies are mutually beneficial; especially strong are the areas of wave interaction physics and chamber studies. Correspondingly, FESAC emphasized two areas of research for "special encouragement in this regard: "theory, including terascale computing, and selected areas of chamber technology." Further, "Specific elements of science and technology critical for evaluating the ultimate energy potential of IFE and MFE, such as interaction of the plasma with chamber walls, should be brought to comparable levels of maturity."

The Integrated Program Plan (IPP) integrates MFE and IFE in a new and consistent way, providing a common planning formalism.

Integration of the U.S. Domestic Fusion Program and the World Fusion Program

FESAC has highlighted the U.S. role in the international fusion program: "The large international MFE program, over a billion dollars per year, provides important opportunities to US researchers. The portfolio of US investments is chosen to benefit maximally from the international effort, by complementing those efforts. By the same token, the major foreign facilities provide important opportunities for US MFE researchers to perform experiments, collaboratively, which are not possible on domestic facilities. The goals, balance considerations and recommendations provided in this report have been formulated to take the above aspects into account."

With the U.S. MFE budget being only ~20% of the world MFE budget, the U.S. program must focus its activities in order to perform high quality work that makes a significant impact on the world program. Recognizing that the largest and most powerful tokamak and stellarator facilities are located abroad, the U.S. strategic plan has chosen an emphasis on understanding and innovation which spans the range of MFE concepts and builds on U.S. strengths of theory, diagnostics, and experiment design and analysis. The U.S.'s theory and small-to-medium-scale facilities provide opportunities for innovation and understanding. International collaboration provides opportunities for extending this work to larger scale. The international collaborations allow the U.S. researchers to both benefit the foreign programs and to bring the international discoveries and developments back to the domestic program. This is especially important in the area of burning plasma science as embodied in MFE Goal 3, which sets a program goal of advancing understanding and innovation in high-performance plasmas, optimizing projected power plant requirements, and participating in a burning plasma experiment. Research in burning plasma physics is fundamental to the development of fusion energy. These high-performance plasmas provide a research tool for extending our understanding of fusion plasmas. The excitement of a magnetically confined burning plasma experiment stems from the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability and plasma control, in a relevant fusion energy regime. Since only the tokamak concept has the technical basis today to move forward with a high gain burning plasma experiment, most of this research in the near term is focused on tokamak experiments.

In the experimental tokamak program, the US' medium-scale tokamaks emphasize understanding of the underlying physics in the areas of MHD, turbulence and transport, wave-particle interactions, and plasma-wall interactions and the application of that understanding to innovation; the US domestic studies benefit from the discoveries and joint experiments with international tokamak programs; US domestic results, including advanced control and enhanced performance scenarios, are then extended via collaboration on international tokamaks that permit studies at larger size and on devices of different configuration. The US medium-scale spherical torus program is beginning exchanges and joint experiments with devices abroad that differ in their configuration, such as proximity of the conducting wall, permitting greater understanding via joint experiments that focus on understanding the differences related to the different configurations. In the theory program, extensive networking permits teaming between world-class experts in the development and testing of theories both against each other and with experimental data. In the U.S. technology program, the US works with international partners to develop technologies that enable experiments, both domestic and abroad; the US also participates in large-scale programs such as magnets and materials development mainly via international collaboration. By these means, the US domestic program is leveraged against the larger programs abroad to both extend US activity to larger scale and to permit US participation in experimental and technological programs that are unavailable domestically.

The approach of integrated domestic and international programs is consistent with the recommendations from the recent series of policy studies. PCAST (Holdren, The U.S. Program of Fusion Energy Research and Development) in 1995 wrote as its first priority: "a strong domestic core program in plasma science and fusion technology, with funds to explore both advanced tokamak research and research on concepts alternative to the tokamak, leveraged where possible on related activities worldwide." In 1997, PCAST (Holdren, Federal Energy Research and Development for the Challenges of the Twenty-first Century) called for significant collaborations with both the JET program in Europe and the JT-60 program in Japan, to provide experience with prototypes for a burning plasma machine and to explore driven burning plasma discharges. In 1999, SEAB (Meserve, Realizing the Promise of Fusion Energy) wrote "Very substantial MFE program – programs with funding that exceeds that of the U.S. – are being undertaken abroad. In light of the worldwide benefits of fusion, the large resource requirements for its development, and the significant MFE programs that exist outside the U.S., the case for the stable and meaningful engagement of the U.S. in international collaboration is compelling."

"Moreover, over the longer term, the U.S. must involve itself in international experiments associated with burning plasmas." Finally, also in 1999, FESAC (Report of the FESAC Panel on Priorities and Balance) emphasized the role of integration with the international program as setting the pace for the U.S. MFE program: "In the five-year time frame, the international fusion community will be making construction decisions for major next-step experiments. The MFE plan assures that the U.S. remains actively engaged with the international community and is able to participate in a meaningful way with the worldwide development of magnetic fusion energy."

In the next five years, there are two primary options for major next-step MFE burning plasma experiments. The current ITER partners (Europe, Japan and Russia) have developed a design of a smaller next-step experiment called ITER-FEAT which could be constructed at a lower cost. If this international consortium decides to proceed with construction, it will very likely present an opportunity for U.S. participation which would need to be seriously considered. In 1999, SEAB (Meserve, Realizing the Promise of Fusion Energy) wrote: "If [the ITER partners] decide to go forward, the U.S. should seek to participate in some fashion. If they do not, the U.S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost." This strategic approach was also recommended by FESAC in 1998 (Grunder, January 1998, DOE/ER-0720) which wrote: "This effort should be directed at examining lower cost, reduced scope options in the interest of achieving a fusion energy-producing experiment on the fastest possible schedule. These options provide a contingency plan that will be necessary in the event that the financial commitments cannot be secured for the full-mission ITER machine." Following these recommendations, the U.S. MFE program has been assessing other, smaller next-step burning plasma experiments (presently represented by the FIRE design) which would be available for international participation if construction of ITER-FEAT is not undertaken.

The U.S. IFE Program will also benefit from international activities in inertial fusion. Although the worldwide program in inertial fusion is smaller than that in MFE, several major facilities are currently in operation or under construction. The French CEA is planning to construct the LMJ, a megajoule laser facility very similar to NIF with 240 beams compared to NIF's 192 beams. A prototype beamline for the LMJ, the LIL, will be completed in CY2002. LIL will provide valuable performance information for both NIF and LMJ. The major current international ICF facility is GEKKO XII in Osaka, Japan. Work on GEKKO focuses on direct drive ICF. There are several facilities worldwide for short pulse high-intensity laser plasma interaction experiments.

3.0 FESAC Key Issues, Goals, Objectives and Implementation Approaches (Level 2)

This section provides the Level 2 of the Integrated Program Plan. This is based on the key issues, goals and objectives developed by FESAC. Emphasis is placed on the five-year objectives while keeping in mind the longer term objectives. A summary of the six major FESAC goals and their supporting objectives are given in Table. 3.1. These goals and objectives were developed by FESAC assuming modest growth in MFE and IFE funding to a level of about $300M per year. Beyond the five-year goals listed in column 2, the MFE goals were subdivided into 10-year and 15-year goals while the goals adopted for IFE were listed as medium term up to 20 years.

Table 3.1 The Program Goals and Objectives.

Goals	5-Year Objectives	10-Year Objectives	15-Year Objectives
Goal 1: Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.	**1.1 Turbulence and Transport** Advance scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems. **1.2 Macroscopic Stability** Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects. **Develop qualitative predictive capability** for transport and stability in self-organized systems. **1.3 Wave Particle Interactions** Develop predictive capability for plasma heating, flow, and current drive, as well as energetic particle driven instabilities, in a variety of magnetic confinement configurations and especially for reactor-relevant regimes. **1.4 Multiphase Interfaces** Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes. **1.5 General Science** Advance the forefront of non-fusion plasma science and plasma technology across a broad frontier, synergistically with the development of fusion science in both MFE and IFE.	**Develop fully integrated capability** for predicting the performance of externally-controlled systems including turbulent transport, macroscopic stability, wave particle physics and multi-phase interfaces. **Advance the forefront of non-fusion plasma science and technology** across a broad frontier, synergistically with the development of fusion science.	**Develop a fully validated comprehensive simulation capability** applicable to the broad range of magnetic confinement configurations. **Advance the forefront of non-fusion plasma science and technology** across a broad frontier, synergistically with the development of fusion science.

Goal 2: Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.	**2.1 Spherical Torus** Make preliminary determination of the attractiveness of the Spherical Torus (ST), by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths much greater than energy confinement times. **2.2 Reversed Field Pinch** Begin determination of the attractiveness of the Reversed-Field Pinch (RFP) by assessing self-consistent confinement and plasma current sustainment. **2.3 Stellarator** Determine the performance of a large stellarator in the areas of confinement, stability, sustainment and divertor physics through international collaboration. **2.4 Concept Explorations** Resolve key issues for a broad spectrum of configurations at the exploratory level.	**Assess the attractiveness of extrapolable, long-pulse operation of the Spherical Torus** for pulse lengths much greater than current penetration time scales. **Complete determination of the attractiveness of the Reversed-Field Pinch** by investigating high-beta stability, sustainment and plasma-wall interaction. **Determine attractiveness of a Compact Stellarator** by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3-D divertor operation. **Make preliminary determination of the attractiveness of further configurations,** as appropriate. **Resolve key issues** for an extended spectrum of configurations at the exploratory level.	**Assess the attractiveness of one or more of the previously investigated configurations** at the extended performance level. **Make preliminary determination of the attractiveness of further configurations.** **Resolve key issues** for an extended spectrum of configurations at the exploratory level.

Goal 3: **Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.**	**3.1 Profile Control** Assess profile control methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak, consistent with efficient divertor operation, pulse lengths much greater than energy confinement times. **3.2 High Beta Stability and Disruption Mitigation** Develop and assess high-beta instability feedback control methods and disruption control/amelioration in the Advanced Tokamak, for pulse lengths much greater than energy confinement times. **3.3 Burning Plasma** Develop and assess burning plasma scenarios and potential next step burning plasma options utilizing domestic resources and working in concert with international collaborators.	**Assess the attractiveness of extrapolable, long-pulse operation of the Advanced Tokamak** for pulse lengths much greater than current penetration time scales. **Assess potential of Spherical Torus** as a basis for burning plasma studies and/or fusion-nuclear component testing. **Participate in an international collaboration** to construct a high-gain burning plasma experiment.	**Demonstrate high-gain burning plasma operation in a plasma regime** relevant to the practical production of fusion power.

<u>Goal 4:</u> Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.	**<u>4.1 Plasma Technologies</u>** Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma measurements, heating, current drive, and fueling; develop plasma facing components; study improvements in magnet technology which could lead to significant reductions in the cost of fusion systems**.** **<u>4.2 Advanced Design</u>** Perform a range of advanced MFE and IFE design studies to support the goals of the scientific program; assess the role of fusion energy in the context of all energy systems. **<u>4.3 Fusion (Chamber) Technologies</u>** Demonstrate the scientific feasibility of innovative plasma chamber technologies for magnetic fusion energy; develop the database that demonstrates the safety aspects of fusion, including the ability to handle and process fusion fuels; assess facilities needs for this development, including opportunities for international collaboration. **<u>4.4 Materials</u>** Advance the materials science base for the development of innovative materials and fabrication methods that will enable improved performance, enhanced safety, and reduced overall fusion system costs so as to permit fusion to reach its full potential; assess facilities needs for this development, including opportunities for international collaboration; support materials research needs for existing and near-term devices.	**Continue to develop required enabling technologies**. **Resolve key feasibility issues for new and improved materials and technologies** by testing and computation.	**Test attractive materials and technologies** in a realistic fusion environment. **Participate in the operations of an international fusion test facility.**

Goals	5-Year Objectives	Medium Term to 20 Years
Goal 5: Advance the fundamental understanding and predictability of high energy density (HED) plasmas for IFE, leveraging from the ICF target physics work sponsored by the National Nuclear Security Agency's Office of Defense Programs.	**5.1 Beam Target Interaction and Coupling** Advance the understanding of driver interaction and coupling in IFE targets to a level sufficient to determine tradeoffs among driver beam focusing, absorption, x-ray production, beam-plasma instability, and target preheat. **5.2 Energy Transport and Symmetry** Advance the understanding of energy transport to a level sufficient to determine the tradeoffs between the number of beams and chamber geometry, beam spatial profile, beam pointing accuracy and beam power balance, as well as hohlraum geometry for indirect drive. **5.3 Implosion Dynamics and Equations of State (EOS) of Materials** Advance the understanding of implosion dynamics and EOS of fusion materials to a level sufficient to determine the pulse shape and timing requirements for IFE targets. **5.4 Hydrodynamic Instability and Mix** Advance the understanding of hydrodynamic instability and mix sufficient to determine the tradeoffs between techniques to optimize ablation stabilization as well as other approaches to reducing instability growth, and the driver requirements on intensity, spatial uniformity and pulse shaping. **5.5 Ignition and Burn Propagation** Advance the integrated understanding of coupling, symmetry, pulse shaping, and instability sufficient to specify the optimal assembly of fuel for ignition and burn propagation subject to tradeoffs in driver, chamber and target fabrication specifications.	**Develop optimized target designs based on information from the IRE and NIF and other intertial fusion programs.**

Goals	5-Year Objectives	Medium Term to 20 Years
Goal 6: Develop the science and technology of attractive rep-rated IFE power systems leveraging from the work sponsored by the National Nuclear Security Agency's Office of Defense Programs.	**6.1 Heavy Ion Beam Experiments and Supporting Accelerator Technologies** Perform single-beam, high-current experiments to validate ion production, acceleration, and transport in a driver-relevant regime (line charge density 10-100 times higher than in present experiments). Develop technologies to minimize the cost of these experiments and the IRE. **6.2 Integrated Ion Beam Modeling, Focusing and Transport** Complete detailed end-to-end (ion source-to-target) numerical simulations of the IRE and full-scale drivers, including focusing and chamber transport, and compare model prediction with experiments in heavy-ion beam acceleration, drift compression, focusing and chamber transport. **6.3 KRF Laser Driver Development** Build and test a >400-700 joule Krypton-Fluoride laser experiment capable of >6% wall plug efficiency, a single-beam nonuniformity <1%, at 5 Hz pulse-rate for $>10^5$ shots, in a laser architecture that extrapolates to < \$400/joule for a power plant driver. Perform additional KrF development required for a KrF IRE decision: KrF physics, improved direct-drive target design, advanced front end for pulse shaping and zooming, improved optics coating for high damage threshold mirrors, and systems analysis. **6.4 DPSSL Laser Driver Experiment** Build and test a >100 joule Diode Pumped Solid State Laser (DPSSL) experiment capable of >10% (1ω) wall plug efficiency, a beam nonuniformity on target < 0.1 to 1%, at 10 Hz pulse-rates for $>10^8$ shots, in a laser architecture that extrapolates to < \$400/joule for a power plant driver. Perform Supporting DPSSL research needed in addition to a DPSSL experiment: lower cost diodes, improved DPSSL IFE target designs, improved crystal growth, and system integration and	**Demonstrate that ion beams and lasers can be focused on a target** in a reactor relevant chamber several times a second with sufficient intensities to obtain moderate gain in an Engineering Test Facility (ETF) **Demonstrate that a rep-rated final-focus magnet/optics system can successfully operate** in the radiation environment characteristic of an ETF **Demonstrate the injection of both direct and indirect drive targets** into a reactor relevant chamber and the low cost manufacture of about 10,000 representative targets. **Demonstrate that reactor relevant materials can successfully operate** after exposure to 10% of the goal of neutron, x-ray, and target debris exposure expected in an ETF **Qualify materials for candidate ETF chambers** than can meet current safety and environmental standards **Carry out ETF design studies** **Complete the IRE program** to provide the economic, scientific, and technological foundations for full-scale driver construction, allowing down-selection of options.

	scaling. **6.5 IFE Chamber and Target Research** Demonstrate feasibility of chamber clearing for thick-liquid-wall chambers, dry-wall chamber concepts that are tolerant of uncertainties in response of materials to fusion pulse and radiation damage, plausible designs for protecting final focusing elements for ion accelerator and laser drivers. Use existing pulsed x-ray z-pinch sources to study x-ray material response of IFE chamber materials. Evaluate safety and environmental aspects of IFE power plants and modify designs such that plants can meet the no-public-evacuation safety criteria, and credible pathways to low-cost target fabrication, accurate injection, and target survival through experiments and analyses. **6.6 IFE Concept Exploration** Concept exploration (CE) level research should be performed on advanced drivers and targets that have potential for major improvements in IFE.	

Before proceeding to the descriptions of the goals and objectives, it is important to emphasize again that the fusion energy quest *demands* excellent science—it will fail without the nourishment of scientific advance and deep scientific understanding. At the same time, the fusion program has an extraordinary record in *generating* excellent science—bringing crucial insights as well as conceptual innovations to such disciplines as fluid mechanics, astrophysics, and nonlinear dynamics. A representative list of scientific questions is in Appendix III in areas of transport and turbulence, plasma fluid behavior, wave-particle interactions, plasma-wall interactions, beam and target physics and fusion technology. Most of the scientific advances engendered by fusion research have begun as discoveries about the behavior of the plasma state of matter.

The central intellectual challenge posed by plasma physics is to find a tractable description of a many-body system, involving long-range interactions, collective processes, and strong departures from equilibrium. This challenge has stimulated a remarkable series of scientific advances, including the concept of collisionless (Landau) damping, the discovery of solitons, and the enrichment of research in chaos. The success that has been achieved has accelerated in the past few decades. Increasingly, the combination of experiment, analysis, and computation has led to scientific understanding with both explanatory and predictive power.

Wider and more fruitful contact with related disciplines increasingly characterizes fusion research. Some recently proposed confinement schemes, for example, are inspired by astrophysical plasma phenomena. Similarly, advances in understanding plasma turbulence owe much to research in such areas as organized criticality and hydrodynamics. Perhaps most important is the growing community appreciation that improved contact with other areas of physics and science is essential to the continued progress of both MFE and IFE fusion research.

The format for the Level 2 information in this section is as follows:

- a statement of the FESAC goal followed by an explanatory description;
- a statement of its supporting objectives;
- an indication of how progress will be measured for each objective;

- a discussion of each objective including key issues; and
- a list and description of implementation approaches for each objective.

3.1 MFE Goal 1: Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

In formulating this goal, FESAC acknowledges that the quest for fusion power "will fail without the nourishment of scientific advance and deep scientific understanding." Fusion research has a long history of contribution to fundamental physics, involving such areas as collisionless (Landau) damping, soliton physics and magnetic field chaos. The advance towards a fusion reactor will require numerous scientific advances of similar depth and importance. Indeed, such relatively recent discoveries as those associated with turbulent transport, transport barriers and the effects of magnetic-field and velocity shear, while not yet fully understood, seem likely to carry fundamental and widely applicable significance.

Within the goal of scientific understanding, FESAC identified five more specific scientific areas. Identified as near-term objectives, the five areas also form the foundation for longer-term fusion progress. These are (i) turbulence and transport, (ii) macroscopic stability, (iii) wave-particle interaction, (iv) edge physics, and (v) general plasma science. Here we consider each of the five areas in turn. After reviewing the five-year objective enunciated by FESAC for each, we describe its broad scientific significance (including how progress will be measured) and discuss for each the tools and methods recommended for scientific progress.

3.1.1: TURBULENCE AND TRANSPORT

What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled?

5-Year Objective: Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems.

Progress will be measured by the evolving level of agreement between theory, simulation and experimental measurements of transport phenomena.

Description and Key Issues:

Plasma transport---the diffusion of particles, momentum and heat across the magnetic field of a magnetic confinement device---has been a controlling issue in fusion research since the first confinement experiments. Transport occurs in a quiescent plasma because of Coulomb collisions, which jar particles from their magnetic field-line orbits. However, observed transport levels generally exceed the collisional rate by orders of magnitude, because confined plasmas are usually turbulent. Predicting the properties of turbulent transport is a profound issue in several areas of physics, including hydrodynamics and astrophysics. Therefore, the progress fusion scientists have made in this area is profoundly important. But the design and operation of future devices will increasingly depend upon the ability to predict transport with quantitative accuracy, and this ability will require deeper understanding of turbulent mechanisms and effects. Key transport issues include more complete understanding of the underlying processes responsible for transport barrier formation and evolution seen in experiments, and the need to understand electron transport more deeply.

Implementation Approaches:

3.1.1.1 Predictive Capability: Use advanced fluid and kinetic simulations, benchmarked by analytic theory and experiment, to develop a first-principles-based predictive capability for core transport in turbulent, magnetized plasmas. Enhance diagnostic capability in order to test relevant details of the theoretical models. Identify key scale-lengths and universal characteristics of turbulence. Bring understanding of electron thermal transport to a level comparable to that of ion transport. Verify accuracy of neoclassical description during quiescent operation.

3.1.1.2 Understanding Transport Barriers: Develop understanding of transport barriers and their relation to magnetic shear and velocity shear. Identify key data needed to verify shear-flow theories of turbulence reduction. Determine electromagnetic effects on turbulence and its suppression. Establish scale-lengths and power thresholds for barrier formation.

3.1.1.3 Integrated Models of Core and Edge Physics: Develop integrated models for core transport and edge physics, including relevant atomic processes, divertor geometry and wall interactions. Determine conditions for validity of confinement scaling laws, and improve understanding of their relation to first-principles transport descriptions. Develop understanding of confinement-geometry effects (such as plasma aspect ratio, elongation, triangularity, and scale lengths) on turbulence and transport.

3.1.2: MACROSCOPIC STABILITY

What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems?

5-Year Objective: Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects.

Progress will be measured by the level of agreement between predicted and observed stability regimes and by improvements in the stability of operating confinement devices.

Description and Key Issues:

Macroscopic plasma motions are those in which the scale lengths of the perturbed electromagnetic field are large compared to particle Larmor radii, sometimes on the scale of the confining system. Most such motions are well described by magnetohydrodynamics (MHD), in either its ideal or dissipative versions. The plasma response to MHD instability can be dramatic and sometimes catastrophic; in a disruption, for example, the plasma is quickly driven to the container walls. But even milder expression of macroscopic instability critically affects the quality of magnetic confinement, by setting limits on the thermal energy that can be confined at a given magnetic field strength. This crucial aspect of confinement quality is measured by beta, the ratio of plasma thermal energy (pressure) to confining field energy. If adequate confinement can be obtained, then no other physics parameter has a more direct impact on fusion reactor efficiency than beta, and the primary limitation on beta usually comes from macroscopic stability. MHD stability is also closely tied to issues of creating and sustaining certain magnetic configurations, especially with regard to steady-state operation.

Although a wide range of magnetic configurations exist, the underlying MHD physics is common to all. Understanding of MHD stability gained in one configuration can benefit others, by verifying analytic theories, providing benchmarks for predictive MHD stability codes, and advancing the development of active control techniques.

Three classes of macroscopic instability require particular attention: ideal modes, some limits of which are now understood well enough to allow reliable predictions; resistive wall modes (resulting from the finite skin time of the plasma containing wall), which are well understood qualitatively but await full quantitative predictability; and kinetic instabilities, such as the “neoclassical tearing mode,” whose importance is established but whose detailed properties are not yet fully understood.

Implementation Approaches:

3.1.2.1 Understanding Observed Macroscopic Stability Limits: Extend present close agreement between ideal stability limits and experiments at extreme (large or small) mode numbers to the intermediate mode-number case. Advance nonlinear understanding of plasma deformation with unit poloidal and toroidal mode numbers. Develop theory of resistive wall modes, and support their experimental investigation on both tokamaks and reversed field pinch devices. Improve usefulness of resistive instability predictions through extended theory and simulation, and by including additional physics in fluid models.

3.1.2.2 Understanding Physics Underlying External Stability Control: Understand stability consequences of appropriately shaping the plasma boundary. Improve and validate theoretical understanding of three-dimensional magnetic structures, involving either asymmetric equilibrium fields or finite magnetic perturbations of axisymmetric geometry. Enlarge understanding of how pressure, density and temperature profiles affect macroscopic stability. Further develop theories of feedback stabilization; support their experimental realization and validation. Refine understanding of rotation effects on resistive wall modes. Study and assess various means, such as impurity injection, for mitigating effects of plasma disruption.

3.1.2.3 Extending MHD Description: Develop systematic basis for incorporating finite Larmor radius effects, including neoclassical processes, into fluid models. Understand stability consequences of long mean-free-path physics parallel to the magnetic field. Further enlarge understanding of instabilities driven by suprathermal particles; in particular, improve understanding of Alfvénic instabilities, perhaps by means of fluid-kinetic hybrid descriptions.

3.1.3: WAVE-PARTICLE INTERACTIONS

What are the fundamental causes and nonlinear consequences of wave interactions with thermal and non-thermal particles?

5-Year Objective: Develop fundamental understanding of plasma heating, flow, and current drive, as well as energetic particle driven instabilities, in a variety of magnetic confinement configurations and especially for reactor-relevant regimes.

Progress will be measured by increased level of agreement among theory, numerical simulation, and experiment for understanding and controlling wave-particle phenomena.

Description and Key Issues:

The dynamical behavior of plasmas is often governed by collective phenomena involving exchange of energy or momentum between plasma species and waves (either internally or externally generated). External wave-based methods for plasma heating, flow generation, non-inductive current generation, and instability suppression have become tools for increasing plasma performance through the control and modification of density, temperature, rotation, current, and pressure profiles. Supra-thermal ions (or electrons), created by high-power heating or fusion reactions, can deleteriously influence plasma stability and confinement. Thus, this area offers two key challenges: on the one hand, we should fully exploit wave-particle interaction as a means for controlling plasma parameters; on the other hand, we need to avoid the dangers of unstable interaction between suprathermal fusion products and Alfvén waves.

Implementation Approaches:

3.1.3.1 Plasma Heating and Current Drive: Extend understanding of wave-particle interactions to plasmas with high dielectric constants as well as to reactor-class plasmas. Improve numerical codes to simulate and predict wave propagation, absorption, and mode conversion in 2D and 3D inhomogeneous plasmas. Enlarge and refine physical picture of off-axis current-drive and heating, including the longer time-scale phenomena associated with sustained current drive.

3.1.3.2 Energetic Particle Effects on Radial Profiles and Confinement: Develop understanding of plasma response, especially through changes in fast particle radial profiles, to externally driven suprathermal particle populations. Improve understanding of relation between energetic particles and transport barrier evolution. Improve first-principles physics picture of fusion-generated alpha particle confinement, especially in the presence of magnetic ripple. Develop fundamental understanding of modifying phase-space profiles by means of waves, including such concepts as alpha-channeling and bucket transport.

3.1.3.3 Instabilities Affected by Energetic Particles: Develop self-consistent kinetic-MHD theory and simulations for fast-particle-driven instabilities and the associated transport and loss with detailed comparison against experimental results. Understand fundamental nonlinear resonant-particle wave phenomena such as mode saturation, wave-wave coupling effects, and frequency chirping. Improve understanding of interaction between energetic particles and fluid instability, including kinetic ballooning modes and neoclassical magnetic islands. Interpret experimentally observed fast-particle-driven modes such as chirp modes and the fishbone-like burst modes, in terms of detailed plasma dynamics.

3.1.4: PLASMA BOUNDARY PHYSICS

What are the fundamental processes occurring near the boundary of a confined plasma and how can the interaction between the plasma and material surfaces be controlled?

5-Year Objective: Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes.

Progress will be measured by the level of agreement between models of physical processes in the edge region and experimental measurements, and by the capability to control energy and particle exhaust from a hot plasma.

Description and Key Issues:

Contact between a hot plasma and the walls of its container is unavoidable, even when magnetic confinement is fully successful. Such contact can be harmful both to the walls, which are subject to erosion from intense local heating, and to the plasma, which is easily contaminated and cooled by neutrals and impurities. In fusion plasmas, the heat load on material surfaces will be severe and damaging if not carefully controlled. Therefore, most MFE fusion concepts modify the magnetic field near the plasma boundary, diverting the edge plasma to specialized chambers, where wall interaction is relatively isolated and controllable. In such "divertor" configurations the edge region contains a magnetic separatrix, outside of which reside a layer of lower-density plasma and a relatively high proportion of neutrals and impurities. The physics of this scrape-off layer is challenging because of the more complicated magnetic geometry, because atomic and surface physics come into play, and because density and temperature gradients can become exceptionally steep.

Implementation Approaches:

3.1.4.1 Plasma Edge Physics: Develop physics understanding reliably to predict scrape-off layer widths and radial electric fields in the edge region. Develop theory and modeling for plasma transport along the magnetic field over regions in which the collisionality (ratio of mean-free-path to gradient scale-length) shows wide variation. Enhance diagnostics necessary to identify sources of core impurities. Determine effect of non-Maxwellian electron distributions on atomic transition rates. Extend and refine models of plasma radiation and opacity in the presence of sharp gradients.

3.1.4.2 Coupling Between Edge and Core Plasmas: Improve understanding of plasma transport across the magnetic field in the presence of steep gradients and a magnetic separatrix. Develop understanding of the role of edge profile pedestals on core confinement. Develop a coupled core/edge model and code, with radial electric fields, to simulate confinement regime transitions. Develop detailed understanding of what drives an edge-localized mode, including better diagnostics such as detailed current profile measurements in the edge region.

3.1.4.3 Plasma-wall Interaction: Understand the conditions under which the heat flux from the plasma core can be more broadly distributed on vessel walls and divertor. Develop fundamental understanding of conditions for detachment of flowing plasma from the divertor plate. Use materials-physics data to determine level of tritium retention in walls. Refine understanding of atomic and plasma physical processes in sheath regions near confining walls.

3.1.5: GENERAL PLASMA SCIENCE

5-Year Objective: Advance the forefront of non-fusion plasma science and plasma technology across a broad frontier, synergistically with the development of fusion science in both MFE and IFE.

Progress will be measured by the impact of plasma science advances on research in other disciplines, by increased use of plasma technology in various industries, and by the growth in fundamental understanding of the plasma state.

Description and Key Issues:

A plasma is a many-body dynamical system characterized by long-range interactions, a vast spectrum of *collective* degrees of freedom, and strong, even violent, departures from thermal equilibrium. Plasmas fascinate physicists because their rich dynamics occurs on many disparate space-time scales, from micro-instabilities (and its associated turbulence) to large-scale coherent structures (such as solitons). The plasma state has proven to be an ideal arena for studying such phenomena, in part because its very nature allows electromagnetic coupling for diagnosis and control.

In addition to its intrinsic interest, plasma research enjoys a huge variety of scientific and technological applications. Plasma is the prevalent form of matter in the universe: most physical systems, including stars and interstellar space, are made of plasma. Thus many fields of research use the results of plasma physics; increased collaboration between plasma scientists and researchers in other disciplines has engendered major advances on both sides. Examples include solar physics (coronal flares, reconnection, plasma dynamo), astrophysics (high density matter, equations of state, strong-field physics), magnetosphere structure (magnetotail reconnection, substorm prediction) and plasma processing (computer chip manufacture, materials processing, plasma thrusters). These examples occur in both MFE and IFE (see IFE Goal 1).

Implementation Approaches:

3.1.5.l Pursue fundamental research in plasma, as an archetypal complex system, as a medium prevalent throughout the universe and as a source of unexpected scientific discovery. Advance understanding of plasma across its wide ranges of density, temperature and field intensity, exploiting the full array of modern theoretical tools, experimental diagnostics and computational facilities.

3.1.5.2 Improve communication and intensify collaboration with other disciplines of physics, by paying more attention to other scientific activities and by disseminating plasma results more widely and in clearer, less specialized language.

3.1.5.3 Exploit the facilities, simulation codes and conceptual developments of fusion research to attack the most fundamental and broadly applicable issues in plasma research, including turbulence, magnetic field generation, coherent structures and self-organized states and the behavior of matter under extreme conditions.

3.2 MFE Goal 2: Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.

The confinement of hot plasma by a magnetic field depends sensitively on the shape of the tubes of magnetic flux within the plasma containment device. In addition, the degree to which the magnetic field is generated by external electromagnets or by current flowing within the plasma significantly influences the physical phenomena and the technical tools used to produce and to sustain the plasma. The particular arrangement of the electromagnets and the plasma currents distinguish between the magnetic confinement configurations. Most developed confinement configurations have helical magnetic field lines arranged approximately on non-intersecting, nested toroidal surfaces, such as found in the stellarator, tokamak, and reversed-field-pinch (RFP). Since nature allows great flexibility in shaping magnetic fields, there exist a variety of configurations capable of stable, hot plasma confinement. Because the dependence between plasma confinement and magnetic field configuration is complex and scientifically interesting, the MFE approach to fusion energy is carried out through a “portfolio approach,” as described in detail in the FESAC report on *Opportunities in the Fusion Energy Sciences Program.* (See also Fig. 2.2) This document presents a “roadmap” of “stages of development” for fusion energy development that is common for all fusion approaches and magnetic confinement configurations. There is a strong degree of complementarity and commonalty in the scientific issues addressed by the various confinement configurations. (See Fig. 2.5) The study and evaluation of one magnetic configuration enhances our ability to understand and develop other configurations, and many scientific issues are best addressed by approaching the issue with more than one magnetic configuration.

The second MFE goal seeks to establish a fundamental understanding of the relationship between magnetic configuration, high temperature plasma confinement, and the technologies needed to produce and to sustain high-temperature plasma. In the long-term, this understanding will permit a determination of the attractiveness of these configuration options and a resolution of the key scientific issues needed to optimize the MFE approach to fusion energy at an affordable cost.

The near-term objectives of the MFE goal are to contribute information critical to a program assessment in roughly five years. Four five-year objectives have been identified. The first objective is to investigate the attractiveness of the spherical torus (ST) configuration. The ST represents a strongly shaped, low-aspect ratio limit of the axisymmetric torus. As a result, the ST takes most of the physics issues pursued in the tokamak program to the very high beta regime that potentially introduces new physics. The ST configuration allows the strength of the magnetic field produced from plasma current to nearly equal the magnetic field produced by the external electromagnet. The second five-year objective is to assess the self-consistent confinement and sustainment of the reversed-field pinch (RFP) configuration. The magnetic field of the RFP is dominated by strong plasma current that minimizes the resistive dissipation of the plasma current by self-organizing into a relaxed, configuration with helical field lines. Research in the RFP is moving into the area of profile control and optimization which has been the recent focus of the tokamak program. The third five-year objective is to determine the confinement and stability of the large international stellarators through collaboration with the international programs. A stellarator configuration is formed by three-dimensional shaping of the external magnets, and the magnetic field strength produced by plasma current within a stellarator is much less than the field strength imposed by the magnets. The world’s largest stellarator is the Large-Helical Device (LHD) located in Japan. The five-year objective of the US is to collaborate with LHD and incorporate the results from this large experiment into efforts to optimize and to reduce the overall size of stellarator fusion concepts, preparing for planned US experiments. Stellarator research thus shares with the tokamak the thrust toward smaller, more compact, steady-state systems. The fourth five-year objective is to resolve key scientific issues of other, less-developed configurations by well-posed investigations using a variety of small-scale, exploratory experiments and theoretical modeling.

Although each of the five-year objectives described in this section represents a critical step towards reaching the second MFE goal, the research effort used to reach these objectives will also contribute significantly to the other three MFE goals. For example, the experimental investigations from a variety of magnetic configurations help to develop and to test our abilities to predict and to understand the fundamental behavior of high-temperature plasma (MFE Goal 1). Many of the techniques used to optimize the confinement properties and to sustain efficiently the plasma for long pulses of innovative confinement configurations can also be used for advanced tokamaks (MFE Goal 3) and vice versa. Finally, different innovative magnetic confinement configurations encourage use and testing of different innovative technologies (MFE Goal 4). These technologies, when combined with understanding of fundamental plasma confinement properties, lead to an optimized fusion development path.

In the following subsections, each of the four five-year objectives for MFE Goal 2 is described briefly. Each lists the technical and scientific approaches to implement the objective. Preparation during the next five years aimed at implementing the ten-year objectives for MFE Goal 2 are also identified.

3.2.1: SPHERICAL TORUS

5-Year Objective: Make preliminary determination of the attractiveness of the spherical torus (ST), by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths much greater than energy confinement times.

Progress will be measured by the degree of understanding of the processes and techniques that extend plasma pressure, improve plasma confinement, and allow sustained plasmas in a spherical torus concerning candidate devices for studying burning plasmas and/or testing fusion-nuclear components.

Description and Key Issues:

The spherical torus (ST) has been identified as a candidate magnetic confinement configuration that may reduce the cost of fusion energy development. By reducing the toroidal aspect ratio towards its lower limit (when the major radius is nearly equal to the minor radius), the spherical torus permits a very large plasma current relative to the currents flowing in the surrounding electromagnets. The large plasma current may improve plasma stability and confinement at high plasma pressures and reduced magnetic field and may enable a reduced cost development path. A critical scientific challenge during the next four years concerning attractiveness of the spherical torus is to understand how to produce and maintain efficiently the high-performance spherical torus plasmas in modest-size devices for pulse lengths much greater than energy confinement times. Success in this objective will enable the assessment of high-performance spherical torus plasmas for pulse lengths much greater than the current penetration time scales, which is a ten-year objective.

The very high beta at very low aspect ratio also calls for new methods of plasma heating, current drive, and diagnostics and offers new opportunities in the core as well as the edge physics in the ST. The limited space available in the center hole of the ST plasma further requires the elimination of the solenoid magnet for steady state ST devices producing large neutron fluence. Efficient noninductive startup and sustainment is therefore an important research topic for the ST.

Implementation Approaches:

3.2.1.l Achieve Efficient Heat and Particle Confinement: Assess the efficiency of heat and particle containment as functions of externally controllable parameters of strongly heated spherical torus plasmas with high pressure, modest magnetic field and strong field line curvature. Understand core turbulence and effect its suppression to reveal limiting confinement (corrected neoclassical transport) mechanisms under large plasma flow and large flow gradients. However, very high beta also increases the potential virulence of electromagnetic turbulence to challenge the effectiveness of turbulence suppression by sheared flow observed routinely in the tokamak.

3.2.1.2 Verify Stability of Large Scale MHD Perturbations: Characterize the stability of large-scale magnetohydrodynamic fluid perturbations in spherical torus plasmas of high pressure and modest magnetic field with average toroidal betas up to 25% and with self-generated, or bootstrap, current fractions up to 40%, without active control of plasma instabilities and profiles. Assess requirements for plasma profile and large-scale mode control to increase beta, bootstrap current fraction and plasma pulse duration. As the sound speed approaches the Alfvén speed at very high beta, mass flow begins to alter significantly the equilibrium and stability properties of the plasma, challenging the conclusions of static equilibrium, which is well established in tokamak research.

3.2.1.3 Heat High-beta Over-dense Plasmas: Investigate wave-particle interaction resulting from new radio-frequency wave launchers (such as the high harmonic fast wave) to heat and to control plasmas of very high dielectric constant. Assess the integration of intense heating by radio frequency waves and the injection of neutral particle beams in creating and maintaining high-beta spherical torus plasmas. The fast beam ion speed in the ST will far exceed the Alfvén speed, likely enhancing the Toroidal Alfvén Eigenmode instabilities and the associated dispersion of the energetic ions from the plasma core.

3.2.1.4 Test Plasma Startup With Noninductive Techniques: Characterize the integration of noninductive plasma startup via magnetic reconnection such as using Coaxial Helicity Injection (CHI) with other noninductive and inductive current drive techniques. Investigate a number of noninductive techniques to start and to increase the plasma current in ST plasmas while at the same time minimizing magnetic flux and helicity injection.

3.2.1.5 Disperse Edge Heat Flux at Acceptable Levels: Study the dispersion of edge heat flux over a range of externally controllable parameters and estimate the plasma facing component requirements under high heating power in the spherical torus magnetic geometry. Determine the ability for managing intense energy and particle fluxes in the edge geometry and for increasing pulse durations significantly beyond the energy confinement time. Most elements of the physics on the edge open field lines are shared between the ST and the tokamak, while the ST introduces stronger variations of the magnetic field strength along the field lines, that are closer to the magnetic mirror. The "toroidal mirror" configuration also tends to have large flux expansion in the divertor region, likely extending the physics research to new parameter regimes.

3.2.1.6 Integrate High Confinement and High Beta: Test spherical torus plasmas having both high confinement and high beta for times much longer than the energy confinement times, without active stabilization. Determine the ability for extending the established operating regimes towards simultaneously higher confinement and higher beta using active control of plasma instabilities and profiles. Assess the requirements for integrating high confinement and high beta for long pulse durations with and without active control of instabilities and profiles, to prepare for the succeeding implementation of the 10-year ST objectives. Begin to evaluate physics properties and design options for the moderate-pulse burning plasma mission and for the long-pulse component testing mission in support of the Goal 3 ten-year objectives.

3.2.1.7 Explore Spherical Torus Issues in Directed Laboratory Experiments: Use small and mid-sized laboratory experiments to explore and develop understanding of a variety of issues relevant to future development of the ST concept and/or to general plasma science and technology. Some of these issues are: (i) current drive based on novel helicity injection concepts; (ii) extrapolation of ST physics to the limit of near-unity aspect ratio; (iii) nature of the transition region between externally controlled tokamak-like and self-organized spheromak-like behavior as the stabilizing toroidal magnetic field is reduced; (iv) development of radio frequency wave heating, current drive, and diagnostic techniques relevant to over-dense plasmas; and (v) tests of novel technology for plasma-wall interaction control.

3.2.2: REVERSED FIELD PINCH

5-Year Objective: Begin determination of the attractiveness of the reversed-field pinch (RFP) by assessing self-consistent confinement and plasma current sustainment.

Progress will be measured by the degree of understanding of the processes and techniques that improve energy confinement while simultaneously sustaining RFP plasma discharges.

Description and Key Issues:
The reversed-field-pinch (RFP) confines plasma in a toroidal geometry having comparable toroidal and poloidal magnetic field strengths but with both field components in the RFP largely generated by currents flowing within the plasma. As a consequence, the safety factor, q, for an RFP is always less than unity while for the tokamak, spherical torus, and stellarator, q is larger than one. The safety factor is essentially the number of times a magnetic field line toroidally circles the torus for one transit in the poloidal direction. The RFP concept derives its name from the fact that the direction of the toroidal field is reversed on the outer region of the plasma, and this reversal corresponds to a relaxed state of the confined plasma. The self-relaxation of the RFP plasma sustains the magnetic configuration by a dynamo effect and allows scientists the opportunity to observe highly nonlinear plasma processes that occur both in nature and in the laboratory. As a fusion concept, the RFP may have some advantages relative to the tokamak. The magnetic field at the external coils can be low, and the plasma current can, in principle, be increased sufficiently to allow ohmic ignition. Magnetic fluctuations associated with the plasma relaxation process cause significant energy loss. A critical scientific challenge is to reduce fluctuation-induced transport in an RFP. Initial experiments on transport reduction by current profile control have shown promising results although the tearing of the magnetic field lines still leads to much greater losses than observed in configurations with

$q > 1$. While the tokamak studies primarily electrostatic fluctuations, the RFP provides the complementary study of transport driven by magnetic fluctuations. Scaling of the fluctuations and transport to fusion-relevant scales, the embodiment of a divertor, and how to maintain the plasma current continuously with low recirculating power are also critical issues requiring further modeling and experiments. Methods for stabilizing larger-scale core tearing modes in the RFP by current density profile control, and the effects on energy confinement and sustainment of the discharge, need to be developed and tested. Assessing high-beta stability, sustainment and plasma-wall interactions is a 10-year objective.

Implementation Approaches:

3.2.2.1 Understanding How Current Profile Modifications Can Improve Confinement: Investigate new methods to improve confinement through profile control in an RFP. Determine the lower limit to magnetic fluctuations and transport, and compare new methods for current-profile modification, such as electrostatic current injection and lower hybrid current drive, to transient inductive current profile control. Both the tokamak program and the RFP program are pursuing similar methods of confinement improvement. Complete detailed core fluctuation measurements and well-diagnosed transport experiments to improve understanding of the basic transport mechanisms.

3.2.2.2 Efficient Steady-state Current Drive: Test oscillating field current drive in a high-temperature RFP with low resistance by injecting magnetic helicity into the plasma by applying oscillating toroidal and poloidal loop voltages. Measure the resulting plasma relaxation processes and conduct experiments to determine the current drive efficiency and to examine whether the technique affects confinement. Oscillating field current drive is another method of helicity injection, which is also being studied in the ST and spheromak.

3.2.2.3 MHD Configuration Optimization: Investigate theoretically or with small-scale experiments how the RFP configuration may be improved with modified geometry (aspect ratio and shape), profile control (of current, pressure, flow profiles), or applying an external transform.

3.2.2.4 Reversed Field Pinch 10-year Objectives: Prepare for experimental tests of beta limits, feedback stabilization, and plasma wall interaction control. Perform studies and plan techniques to implement these 10-year RFP objectives.

3.2.3: STELLARATOR

5-Year Objective: Determine the performance of a large stellarator in the areas of confinement, stability, sustainment and divertor physics through international collaboration.

Progress will be measured by the degree by which new results obtained through international collaboration are used to improve the understanding of stellarator confinement, stability, sustainment, and divertor physics and the resolution of key scientific issues and the beginning of construction of a Proof of Principle compact stellarator experiment in the United States.

Description and Key Issues:

The stellarator is a configuration in which the external coil set supplies not only the toroidal magnetic field but also all or much of its poloidal magnetic field. The closed magnetic flux surfaces needed for plasma confinement are created by twisting the shape of the external coils. Because stellarators can be designed with no externally driven plasma current, no recirculating power is needed to support the plasma current. In currentless designs, the optimized stellarator has a large aspect ratio ($R/a \sim 10$), resulting in relatively low power relative to the size of the system. The world's largest stellarator, the Large-Helical Device (LHD), is located in Japan, and scientists will use LHD to investigate plasma confinement in a conventional stellarator at the size-scale comparable to the world's large tokamaks. The five-year objective of the US is to collaborate in understanding the confinement of plasma by the LHD and other experiments, and incorporate the results into efforts to optimize and to reduce the overall size of future stellarator fusion concepts. One promising approach is the compact, low aspect ratio, stellarator, being developed as a possible US experiment. The compact stellarator employs a significant pressure-driven, or bootstrap, current. The self-driven bootstrap current in the plasma provides some of the poloidal magnetic field, thereby relieving some of the nonsymmetry of the confining field coils, and moving the concept away from being purely externally controlled. Critical scientific issues for the stellarator include the identification of optimal configurations for the magnetic field, the confinement and stability of stellarator plasmas at the scales needed for fusion energy, and the accommodation of a divertor for power and particle control that is compatible with nonsymmetry and the limited space between the plasma and the coils. These latter items are 10-year objectives.

Implementation Approaches:

3.2.3.1 Participate in LHD Experiment: Maintain direct scientific participation in the large LHD experiment, located in Japan, and maintain national expertise capable of evaluating LHD results for the purposes of optimizing stellarator confinement configurations. Planned experiments using the large LHD device will contribute to: (i) understanding energy confinement scaling, (ii) understanding energetic ion confinement and the role of electric fields in controlling energetic particle losses and achieving low, neoclassical ripple-induced transport, and (iii) evaluating practical power handling and steady-state performance.

3.2.3.2 Advance Stellarator Physics Using Small, Exploratory Experiments: Use small-scale exploratory experiments to (i) investigate the reduction of neoclassical transport in magnetic configurations with quasi-helical magnetic symmetry; (ii) demonstrate a reduction in the direct loss of ripple-trapped particles; (iii) show that quasi-helical magnetic symmetry leads to decreased viscous damping of plasma rotation on a flux surface; and (iv) test the understanding of current-driven disruptions in stellarators.

3.2.3.3 Advance Stellarator Physics Using Theory: Extend the framework for the interpretation of experiments, develop techniques for extrapolation of experimental results to next-step, larger-scale experiments, and investigation of improved stellarator configurations. These efforts should also contribute to the general development of three-dimensional plasma theory.

3.2.3.4 Resolve Technical Issues Allowing a Decision to Proceed With a Proof-of-Principle Compact Stellarator Program: With the resolution of key scientific issues, design and begin construction of experiments needed to accomplish the ten-year objective of determining the attractiveness of compact stellarators. Define the parameters of compact stellarator experiments having (i) sufficient flexibility to explore a range of the most critical scientific questions, and (ii) sufficient plasma performance and machine capability for integrated testing of a compact stellarator configuration with high beta and bootstrap currents that can form the basis for extrapolation to more reactor-relevant performance.

3.2.4: CONCEPT EXPLORATION

5-Year Objective: Resolve key issues for a broad spectrum of configurations at the exploratory level.

Progress will be measured by the degree that key issues are resolved allowing technical decisions to be made of the readiness to embark on investigations on the proof-of-principle scale.

Description and Key Issues:

There are a number of other configurations which are interesting as scientific research tools and which may have the potential for some near-term applications in science and/or technology, but which are more speculative in regard to their ability to produce net fusion power. Generally, these configurations have unique and challenging physics and technology issues. Exploratory concept research programs aim to resolve selected key questions, to advance fundamental scientific understanding, and to test innovative ideas. They consist of small-scale experiments usually strongly coupled with theory and strive at establishing the basic feasibility of a concept and/or exploring certain phenomena of interest and benefit to other concepts. Since these concepts are exploratory, basic questions exist about confinement, gross MHD stability, formation, and sustainment of the plasma equilibrium. Nevertheless, these configurations may represent an attractive alternate approach to particular fusion power applications.

At the present time, configurations studied at the exploratory level are broadly classified into two types: (i) self-organized, compact toroidal configurations, and (ii) other innovative and/or very new magnetic fusion concepts. A competitive scientific peer-review process reviewed and recommended these experiments based on the scientific merits of each proposal. The first category includes the spheromak and the field-reversed-configuration (FRC). Like the RFP, the magnetic fields created in these configurations are produced primarily by internal plasma currents. However, the spheromak and the FRC do not have electromagnets located along their axes. The overall shapes of the plasmas confined by these devices are spheres or ellipsoids, and these shapes significantly simplify the interface between the plasma and the outer material boundary. These shapes also allow an extra degree of freedom and the occurrence of additional macro-instabilities, which need to be evaluated. The second category includes a wide-variety of new and less-developed fusion concepts such as the levitated magnetic dipole configuration, magnetized target fusion, configurations with strongly-rotating plasma flows, and the Penning trap with oscillating electrostatic potentials.

Implementation Approaches:

3.2.4.1 Resolve Key Issues of the Spheromak Configuration: Study spheromak sustainment, stability, and confinement in plasmas with electron mean-free-paths comparable to machine dimensions, requiring temperatures of a few hundred electron volts in a spheromak sustained for several energy confinement times. Investigate the physics of energy confinement in the presence of the magnetic dynamo, especially during sustainment and use this understanding to investigate improved confinement. Understand the coupling of the helicity injector to the spheromak and how to optimize helicity current-drive efficiency. Investigate the effects of low aspect ratio and edge coupled helicity injection on relaxation and confinement. Determine the beta-limiting processes in the spheromak plasma. Measure the processes that determine the properties of the edge/boundary plasma.

3.2.4.2 Resolve Key Issues of the FRC Configuration: Develop the use of rotating magnetic fields to form and sustain FRC with sufficiently low collisionality and high flux needed to study the physical mechanism underlying the experimentally observed FRC stability. Investigate stabilizing mechanisms such as finite Larmor radius effects, kinetic effects, and two fluid helicity. Investigate the physics of transport, flux decay, and confinement in an FRC.

3.2.4.3 Resolve Key Issues of Levitated Magnetic Dipole Configuration: Create and sustain high-pressure plasma in a levitated dipole, understand the stabilizing effects of plasma compressability, and test the theoretical prediction of the elimination of both MHD and drift-wave instability for sufficiently gentle pressure gradients. Observe the effects of convective cell plasma flows.

3.2.4.4 Resolve Key Issues of Target Formation, Translation, and Physics for Magnetized Target Fusion (MTF): Produce and translate the target plasma required for a MTF experiment capable of establishing whether heating to thermonuclear temperature is possible with liner compression. Further develop understanding of the stability of liner and plasma during compression and wall-plasma interactions throughout the process. Resolve major issues of potential MTF reactors including cost and refabrication of materials that must be processed for each pulse.

3.2.4.5 Resolve Key Issues of the Electric Tokamak (ET): Carry out exploratory experiments toward the goal of achieving a unity beta plasma with greatly improved energy confinement at low magnetic field (0.25 T). Use RF heated energetic ion losses to create and sustain a large radial electric field induced poloidal rotation sufficient to lock the thermal ion orbits to the magnetic surfaces. Test predictions that these high poloidal rotation rates will reduce ion transport to classical levels and will stabilize MHD instability allowing access to very high-beta regimes free of particle curvature drifts. Assess the prospects for new generation of high-density, very high-beta tokamak devices leading to improved fusion power plant designs.

3.2.4.6 Resolve Key Issues of Other Exploratory Concepts: Conduct selected, well-proposed exploratory research to resolve key issues of innovative fusion concepts or to answer key questions pertaining to plasma science issues and/or to other fusion concepts. Many independent experiments and theory activities advancing basic and fusion plasma physics are preferred and can be attempted in parallel, each focusing on a small set of issues. High risk, large payoff research is desirable and should be encouraged. Activities should be of short duration in order to allow for a high turnover rate as part of a peer-reviewed process.

3.3 MFE Goal 3: Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.

High-performance plasmas provide a research tool for extending our understanding of fusion plasmas. These plasmas are characterized by dimensionless parameters such as collisionality, the ratio of the Larmor radius to machine size ($\rho^* = \rho/a$), and β which are approaching those in a power-plant or in a burning plasma. Under these conditions, new physics is encountered ranging from nonlinear and kinetic magnetohydrodynamic instabilities, which affect the plasma stability, to energetic particle collective instabilities, confinement of the alpha particles, and confinement of the thermal plasma at a larger ratio of system size to gyro-radius. The understanding of these high performance plasmas, along with the scientific results form Goal 2, is an important contribution to Goal 1. Furthermore, this understanding enables the innovation to optimize the designs of not only power-plants but also of a burning plasma experiment. The study of high performance plasmas in the domestic program is enhanced by the much larger international effort, which provides a platform for further testing the understanding and innovations obtained on our facilities under even more demanding dimensionless parameters.

Based on the broad base of experience, achievement of reactor-relevant parameters and performance, and the level of scientific understanding; the tokamak is technically ready to go forward with a high gain burning plasma experiment. While the physics basis has been judged sufficient to proceed with a burning plasma experiment for the standard sawtoothing ELM-ing H-mode discharges, it appears from recent theoretical and experimental work that the potential of the tokamak as a magnetic confinement configuration extends considerably beyond the present database. Current tokamak research worldwide is focussing on these exciting possibilities. States of much reduced plasma transport have been discovered in which in the best cases the theoretical minimum ion heat transport owing to Coulomb collisions has been achieved. It appears the physics of these improved transport regimes may be applicable to other magnetic configurations; since the mirror, stellarator, and RFP configurations have shown some evidence of similar effects. These improved transport modes would decrease the size and cost of fusion systems. Theory work has pointed to higher stability states that can enable nearly all the plasma current to be self-generated, an exciting path toward steady-state operation. These states typically require stabilization of the plasma by a nearby conducting wall and active feedback coils, a physics element common to the tokamak, spherical torus, RFP, spheromak, and FRC.

The new challenge posed in the area of heating and current drive is to use the techniques developed for precise control of local plasma profiles to access these advanced plasma states. While a plasma power and particle exhaust solution appears available at high density, a lower density solution must be developed because this general research line moves toward lower density owing to the need for substantial non-inductive current drive. These significant improvements in plasma performance and in the reactor embodiment of the tokamak may be realized by optimizing the tokamak concept through plasma shape control, profile control, plasma boundary control and active MHD feedback control, toward high performance and steady state. Optimization of the tokamak along these research directions is commonly referred to as the advanced tokamak (AT) and many elements of the AT are shared with the spherical torus. These research lines are of fundamental importance and must be carried out to complete the science basis of the tokamak configuration.

The excitement of a magnetically confined burning plasma experiment stems from the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability and plasma control, in a relevant fusion energy regime. This research in burning plasma physics is fundamental to the development of fusion energy. In the tokamak configuration, alpha particle physics in deuterium-tritium (DT) experiments has been studied and DT experiments have produced up to 16 MW of fusion power. The predominant view expressed at the Snowmass Summer Fusion Study was that a burning plasma experiment, based on a conventional tokamak operating regime, needs to be planned in order to: (a) demonstrate the feasibility of a controlled plasma burn; (b) resolve transport, stability and other plasma science issues at large dimensionless scale (a/ρ_i) in a burning plasma regime; (c) develop methods of burn, profile and instability control relevant to high energy gain regimes which are also likely to be applicable to other MFE concepts; and (d) access advanced modes of tokamak operation for concept improvement under burning plasma conditions. All of these must be demonstrated simultaneously with compatible methods of heat and helium ash removal that also would enable reasonable first-wall lifetime.

The research in support of MFE Goal 3 is aimed at preparing the MFE program to be ready to move forward with the next stage of development, by addressing the most urgent issues for the advanced tokamak and by continuing to make progress in the physics understanding of burning plasma issues. In the five-year time frame, the international fusion community will be making construction decisions for major next-step experiments. Through the research outlined in this section and carried out with international collaborations among the major research facilities, the MFE plan assures that the U.S. remains actively engaged with the international community and is able to participate in a meaningful way in this decision process.

In the following subsections, each of three five-year objectives for MFE Goal 3 is described briefly, including the technical and scientific approaches to implement the objective. Each of the five-year objectives described in this section represents a critical step towards reaching MFE Goal 3. In addition, these five-year objectives help prepare us for our longer range objectives (see Table 3.1). It is important to keep the 10 and 15-year objectives in mind, as preparatory work for the 10 and 15-year objectives may need to be addressed explicitly.

3.3.1: PROFILE CONTROL

5-Year Objective: Assess profile control methods for efficient current sustainment and confinement enhancements in the advanced tokamak, consistent with efficient divertor operation, for pulse lengths much greater than energy confinement times.

Progress will be measured by assessing the understanding of the physical processes that govern the plasma profiles and the confidence in the ability to control the plasma profiles in present and next-generation-devices in ways which are consistent with effective divertor operation.

Description and Key Issues:

Enhancement of confinement and stability in tokamak plasmas is most likely achieved by cross-section shaping and careful tailoring of the spatial profiles of the plasma current, the plasma pressure, the plasma flows, and the plasma transport. Recent transient experiments have demonstrated that plasma confinement can be more-than-doubled by the influence of shear in the plasma flow and that pressure limits can be significantly increased by tailoring of the spatial profile of the plasma current density and pressure profile. In steady-state high bootstrap-fraction advanced tokamak scenarios, the current profile is largely determined by the pressure profile, and the pressure profile is determined largely by control of the transport. As transport is affected strongly by current profile, this is a highly nonlinear system. The most advanced equilibria, though at much higher value of beta, projected for the spherical torus share many features in common with advanced tokamak equilibria and the profile control may be very similar. Besides the tokamak, this area of profile control is a newly active area of research in the reversed field pinch, in which auxiliary current drive and manipulation of radial electric fields are being used in ways similar to tokamak research. Assessing profile control and high beta stability in the next five years lays the ground work for extending the advanced tokamak to steady state and to assess the attractiveness of extrapolable, long-pulse operation of the advanced tokamak for pulse length for pulse lengths much greater than current penetration time scales.

The main challenges for current profile control are the ability to localize the current to obtain profiles that are consistent with high beta stability limits and reduced transport. Off-axis current drive must take into account particle trapping and detailed theory/experiment comparison must be advanced to understand the magnitude of the driven current: new measurements of the non-thermal electron distribution are likely required. High gain steady state discharges require efficient current sustainment (low total current drive power) compatible with effective divertor operation to adequately handle the heat removal and maintain plasma purity. A fundamental conflict exists between the desire for low density in the core to maximize the driven current, and the desire for high density in the divertor to assist in radiatively dispersing the heat. Profile control techniques must be developed that are consistent with effective divertor operation, yielding acceptable heat loading and plasma cleanliness, efficient ash particle control, first wall survivability, and acceptable tritium inventory. Operation with significant self-driven plasma current (high bootstrap fraction) reduces the overall current drive power and allows higher density operation, but puts additional emphasis on pressure profile control. The pressure profile is modified by varying the power deposition, particle deposition and transport profiles. The transport profiles are in turn dependent on the current profile (or magnetic shear), the temperature profiles, the density profiles, the plasma flow profiles, and other variables. The strong nonlinear coupling makes the control of the transport and pressure profile complex and detailed models of the partial and complete suppression of turbulence must be developed and validated against experiment. Experimentally, it is observed that the reduction in transport often occurs under different conditions for the electron thermal transport, ion thermal transport, and particle and impurity transport. The theoretical and numerical models must explain the difference. Temporally and spatially resolved profile measurements and new turbulence diagnostic measurements are required to accurately determine this complex transport behavior and differentiate the turbulence mechanisms responsible for the different transport channels together with the profiles of the heating and fueling sources.

Implementation Approaches:

Control of the profiles of plasma current, pressure, flow and transport will be advanced by conducting experiments and developing theories to increase understanding and control the physical processes that determine the spatial distributions. Close attention must be paid to ensure that the techniques are mutually compatible, as well as being consistent with particle and heat removal.

3.3.1.1 Plasma Current Profile: Utilize both transient techniques such as ramping the plasma current and long-pulse techniques such as self-driven plasma current (driven by gradients of plasma density and temperature), neutral beam current drive, and RF-wave-driven current. Develop understanding using detailed diagnostic measurements of the plasma current distribution, models for self-driven plasma currents, the non-thermal distribution of the current carrying particles, as well as plasma-wave interactions. Seek to demonstrate states of higher plasma stability utilizing efficient current drive techniques.

3.3.1.2 Plasma Pressure Profile: Apply localized heating and different particle fueling techniques as well as control of the thermal and particle transport profiles. Develop understanding using space and time resolved diagnostic measurements of the electron temperature, ion temperature, ion density and impurity distributions as well as models for both plasma heating and transport to achieve operating regimes with enhanced confinement and stability.

3.3.1.3 Plasma Flow Profile: Use detailed diagnostic measurements of the plasma flow profiles, including the pressure gradient component, and models for the plasma flow drive, as well as models for transport. Develop externally controlled plasma flow drive techniques.

3.3.1.4 Plasma Transport Profile: Compare measurements of the profiles of plasma current density, pressure, and flows and of plasma fluctuations with predictions of theoretical models for turbulent driven transport and the reduction and suppression of turbulence.

3.3.1.5 Low Density Divertor Operation: Determine techniques for power dissipation and helium pumping which can be maintained as the density is lowered for AT operation.

3.3.2: HIGH BETA STABILITY AND DISRUPTION MITIGATION

5-Year Objective: Develop and assess high-beta instability feedback control methods and disruption control/amelioration in the advanced tokamak, for pulse lengths much greater than energy confinement times.

Progress will be measured by assessing improvements in the level of understanding of the physical processes that govern the stability limits; in the confidence in the ability to control the instabilities to reach higher stability states while avoiding disruptive plasma termination with passive and active feedback control; and in the ability to safely ameliorate disruptions, in both present and next generation devices

Description and Key Issues:

To realize the benefits of steady high performance plasmas in both the advanced tokamak and the ST, operation at high normalized beta (β_N) is needed, typically beyond that obtainable without wall stabilization. Theoretically, stability beyond the no wall beta limit can be maintained without active feedback, provided the plasma rotation is sufficiently high, but it is questionable that such a high rotation can be realized in next step devices. Development of non-axisymmetric active feedback control is then needed to realize the high beta results. Both experimental and theoretical/numerical progress is needed to develop the optimal sensor and feedback coil locations and determine the viability of active feedback of resistive wall modes under reactor conditions, where high neutron flux and the proximity and thickness of the blanket complicate the coil placement.

Neoclassical Tearing Modes, NTM, now set the performance limit in many tokamak operating regimes. The challenge is to develop operational regimes to avoid the instability or actively stabilize the modes. Localized current drive at the rational surface has been shown theoretically and experimentally to stabilize the mode. The challenge is to optimize the active stabilization of the mode and develop active localized current drive feedback techniques and controls. Variation of the radial deposition under feedback control is likely required. Measurement and understanding of both the localized current drive and the nonlinear growth of the mode is needed. The basic physics of the stability of the NTM, particularly its threshold mechanism, must be better understood to allow extrapolation to reactor conditions.

Disruptions and vertical displacement events (VDE) occur when MHD stability limits are exceeded. These limits can be violated in normal operation, which normally has the goal of pushing the plasma pressure up as close as possible to the stability limit, when power balance is violated, or when equilibrium systems fail. A critical issue is how close to the stability limits a tokamak can be operated for long periods of time without disruptions. The main challenge posed by disruptions is to minimize or eliminate the resulting damage to first wall and divertor components from thermal and electromagnetic stresses. Runaway electrons, generated during the decay of the plasma current, pose a potential threat to the first wall and need to be understood from detailed experimental measurements and modeling.

Implementation Approaches:

High beta instability feedback control will be advanced by conducting detailed feedback experiments in medium-scale and supporting Concept Exploration devices and developing theories to increase understanding of the instability boundaries and the techniques to control those instabilities

3.3.2.1 Resistive Wall Mode Control: Apply non-axisymmetric fields to high beta plasmas that are beyond the ideal MHD limit without a conducting wall. Develop detailed understanding of the resistive-wall mode (RWM) instability and to what extent plasma rotation can stabilize the mode, through detailed measurements of the plasma profiles, calculated stability boundaries and mode structure. Develop three-dimensional theories and models of the RWM and determine optimal sensor and feedback coil placement for present and future experiments. Develop and test different feedback control schemes as appropriate. Develop models applicable across magnetic concepts (tokamak, ST, RFP, spheromak, and FRC.)

3.3.2.2 Current Drive Inside Magnetic Islands: Apply localized current drive in high beta plasmas to actively stabilize Neoclassical Tearing Modes in order to achieve values of beta exceeding those obtained at the onset of these instabilities without the application of feedback. Determine the effectiveness as the localization of the driven current within the island center is varied. Make detailed measurements of the island evolution and plasma profile evolution with both co and counter current drive to verify the effectiveness of current drive inside the island. Compare results between experiments at different non-dimensional parameters to better understand the stability boundaries, and physics of the mode. Develop nonlinear, non-ideal theory and three-dimensional codes to understand the island evolution, effectiveness of stabilization, and projection to larger devices with smaller Larmor radius. Apply feedback techniques to other MHD modes, such as locked modes and classical tearing modes.

3.3.2.3 Active Profile Control to Avoid Unstable Boundaries: Use detailed, real time, pressure and current profile measurements, and active control of the current and pressure profile (goal 3.1) to maintain profiles stable to known operational boundaries. Continue development of both ideal and non-ideal MHD models to better define the operational boundaries.

3.3.2.4 Disruption Control/Amelioration: Conduct detailed measurements of the energy and current quench, plasma motion, halo currents, and the resulting thermal and electromechanical impact of disruptions on the first wall and divertor components. Spatially resolved measurements of the energy deposition are needed to determine the wetted area on the divertor plates, and in particular, whether the SOL width increases during a disruption. Strain and/or displacement measurements are needed to confirm electromagnetic models. Develop full three-dimensional models and codes to understand and compare results at different aspect ratios, elongations, divertor geometry, and up-down vertical balance. Knowledge of the dependence of quench rates, halo currents, forces, and thermal energy deposition, from both empirical scaling and modeling, is required to confidently scale to reactor regimes. Continue developing and testing strategies to mitigate the effects of disruptions and VDE's, including forced quench acceleration (killer pellets, liquid jets) and passive stabilization (neutral point operation). Continue experimental and theoretical work on the avoidance of runaway electrons during the current quench.

3.3.3: BURNING PLASMA

5-Year Objective: Develop and assess burning plasma scenarios and potential next step burning plasma options utilizing domestic resources and working in concert with international collaborators.

Progress will be measured by the technical readiness of next step options for a burning plasma physics experiment.

Description and Key Issues:

There are a number of unresolved physics issues that can only be fully addressed in next-step burning plasma experiments. They include burn control, fast particle driven instabilities, transport barrier dynamics at large scale and with dominant self-heating, particle fueling and ash control, power handling, and plasma physics at fusion parameters (β, ν^* and ρ^*). The most challenging issue of burning plasmas is the complexity due to self organization that is present in alpha-dominated plasmas where alpha heating, bootstrap current, MHD stability and transport barriers are strongly coupled. Since comparisons of data among the full range of devices are necessary to resolve such issues as scaling of confinement on dimensionless parameters, these issues will be investigated in the near term, to the extent possible, on existing domestic facilities and through international collaboration on larger devices.

The physics basis of the tokamak concept is largely sufficient to proceed with a next step experiment to evaluate burning plasma physics. The physics basis of the conventional tokamak is sufficient to form the basis for a conservative design, whereas the physics basis for more advanced designs (with profile control, transport barriers, and feedback stabilization of MHD modes) is not yet ready to form the basis for a design, but is sufficient to identify the flexibility needed to accommodate more advanced scenarios and to predict enhanced performance possibilities.

Experiments on existing and enhanced medium- and large-scale tokamaks will further develop the advanced tokamak basis on the five and ten year time frame. Major upgrades to the JET and JT-60U facilities are under consideration. The JET tokamak in Europe will be enhanced to higher heating power allowing more extensive tests in DD of advanced physics scenarios at large scale. The enhanced JET will have the potential of sustained fusion gains approaching unity. A modification of JT-60U is under consideration that would provide increased capabilities for studying advanced tokamak regimes for times long compared to the plasma current redistribution time. The KSTAR device which is under construction in South Korea will investigate long-pulse tokamak physics. The U.S. should be an active participant in this international research program.

Various design options are being pursued, both domestically and internationally, and the physics basis for each option needs to be strengthened. At least two major tokamak approaches are the focus of significant design efforts: the long pulse, superconducting option, presently embodied by the ITER FEAT, and the shorter pulse, higher field, compact copper coil option such as FIRE and IGNITOR. Next step burning plasma experiments should be designed with the flexibility to incorporate advanced tokamak features and thereby extend advanced tokamak concepts into the burning plasma regime. Continued research on existing tokamaks is required to extend existing understanding of advanced tokamak scenarios and provide information to optimize burning plasma experiments. Although the physics basis of the spherical torus is much less advanced, an assessment of its potential could be addressed to a lesser extent in a 5-year period and more fully in the 10-year time frame.

Our 10-year objective is to participate in an international collaboration to construct a high-gain burning plasma experiment. Progress on the 10-year objective will be measured by the state of the designs of burning plasma experiments and by the level of international agreement and commitment to proceed.

Implementation Approaches:

Experiments and design studies focused on resolving key issues pertaining to next step burning plasma tokamak design options will be carried out both domestically and through international collaboration.

3.3.3.1 Coordinated and Joint Experiments: Exploit the capability of existing and upgraded tokamaks to explore and establish operating regimes suitable for burning plasma experiments, and to better develop the scientific basis for next step burning plasma experiments. Complete joint and coordinated experiments on US and international facilities using common experimental techniques, measurements, and analysis to help resolve critical physics issues. Use participation on larger international tokamaks to resolve physics issues that depend on device size or ρ^*, and to evaluate fast particle driven instabilities as appropriate.

3.3.3.2 Prepare for DT experiments to be carried out on the enhanced JET: Complete joint and coordinated experiments on US facilities and the JET tokamak to optimize operational scenarios for a later DT campaign on JET. Develop theory and modeling to evaluate DT performance and advanced tokamak physics. Use detailed measurements on JET, and validated codes to evaluate alpha physics issues and advanced tokamak issues, and their use for extrapolation to the next step.

3.3.3.3 Continue conceptual design work and trade-off studies for next step devices to best understand key issues that need to be addressed, and to be ready to move forward with participation in a next step burning plasma experiment.

Since the international strategy for magnetic fusion is evolving rapidly in the area of burning plasma experiments, this effort needs to be carried out in concert with the international parties and should be ready to move forward at a pace consistent with international activities and changing external conditions.

3.4 MFE Goal 4: Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.

Plasma technologies enable existing and near-term plasma experiments to achieve their scientific research and performance goals. The activities carried out in area of Plasma Technologies support the achievement of other program Goals, most notably Goals 1,2 and 3, by providing essential technologies for use in the experimental programs necessary for the achievement of those Goals.

Advanced design and system studies help shape the directions of the fusion energy sciences program by examining the technical, safety, and economic potential of specific concepts. The activities carried out in pursuit of this objective provide critical guidance to the activities being pursued for all other Goals.

Fusion technologies provide key innovative improvements that will allow fusion to reach its ultimate potential as an energy source. The activities in this area include developing the ability to handle the critical interface between the fusion plasma and surrounding structures, developing the necessary technology to handle and process the fusion fuel, and demonstrating the safety and environmental attractiveness of all fusion systems. The activities carried out in pursuit of this goal are also essential to the accomplishment of MFE Goal 3 and IFE Goal 2.

One of the primary constraints for the development of fusion as an energy source is the qualification of materials for the in-vessel systems that will provide high performance and exhibit favorable safety and environmental features. Structural materials must operate at elevated temperatures for extended lifetimes under severe conditions characteristic of a fusion power system, including high fluxes of high energy (14 MeV) neutrons, high surface heat fluxes, and high temperature coolants and breeding materials. The activities carried out in this area are also essential to the accomplishment of MFE Goal 3 and IFE Goal 2.

3.4.1: PLASMA TECHNOLOGIES

5-Year Objective: Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma measurements, heating, current drive, flow control, and fueling; develop plasma facing components; study improvements in magnet technology which could lead to significant reductions in the cost of fusion systems**.**

Plasma technologies enable existing and near-term plasma experiments to achieve their scientific research and performance goals. They include plasma heating and current drive technologies that are essential for raising plasma temperature and manipulating plasma properties to access advanced operating scenarios (e.g., reversed shear, MHD stabilization, turbulence suppression); fueling technologies, to achieve relevant plasma parameters, such as plasma density and to achieve desired operating scenarios, such as reduced transport; plasma facing components with desired characteristics, such as high heat flux and low erosion and for control of edge plasma conditions and for power and particle control; and new and improved instrumentation for plasma diagnostics and control. Magnets provide the confining force for plasmas in magnetic fusion devices and are a major cost for fusion device construction.

Progress will be measured by the achievement and demonstration of specific component operational parameters, as defined by scientific program needs.

Description and Key Issues:
The main issues for heating and current drive are the development of higher power components (e.g.,gyrotrons, launchers), improved reliability and efficiency of delivering power to the plasma, and real time control of heating and current density profiles.

The main issues for fueling technologies are to understand and exploit advanced fueling physics (such as high field side launch) and demonstrate the performance (i.e., pellet speeds, density of compact toroids and repetition rates) required to effect adequate control of the density profile shape and high fueling efficiency.

The main issues for plasma facing components are to understand, ameliorate, and exploit the interactions between the plasma and the wall and components that surround it and to develop power removal systems that are consistent with high heat flux, high temperature, low erosion and plasma compatibility.

The main issues for magnet development are achieving higher fields, higher current density and higher critical temperatures, while striving to reduce size and cost.

Implementation Approaches:

3.4.1.1 Plasma Heating and Current Drive: For ECH/ECCD, develop multimegawatt, steady-state gyrotrons in the 110- to 200-GHz range; with source efficiency improvements from present 30% to over 75%; develop and test vacuum windows that can transmit 3 MW of power; develop tunable gyrotrons and steady-state rotatable launchers. For ICH/LH, develop improved ion cyclotron and lower hybrid frequency systems emphasizing higher power density, real time phase control and reliable and efficient delivery of power during rapidly changing plasma conditions.

3.4.1.2 Fueling Technologies: Develop systems and fueling techniques that are capable of providing a reliable, flexible particle source for controlling core plasma density and density gradients at acceptable fueling efficiencies; develop technologies for injection of non-hydrogenic materials for diagnostics and disruption mitigation; explore the feasibility of compact, low mass inventory pumping schemes.

3.4.1.3 Plasma Facing Components: Study and characterize materials and plasma materials interaction processes to determine properties such as plasma erosion mechanisms and rates, hydrogen retention and release, impurity generation and transport, and heat and particle removal. Develop innovative plasma facing component with substantial improvement in heat flux/erosion and deploy on fusion devices.

3.4.1.4 Magnets: Improve fabrication techniques; examine fusion applications of higher temperature superconductors; continue to participate in developing advanced high field, low cost superconductor and normal conducting materials, advanced structural and conduit materials, improved conductor joints, and advanced quench detection and protection systems.

3.4.2: ADVANCED DESIGN

5-Year Objective: Perform a range of advanced MFE and IFE design studies to support the goals of the scientific program and identify high-leverage R&D areas; and to assess the role of fusion energy in the context of all energy systems.

Advanced design studies are needed when fusion concepts reach the “proof-of-principle” stage in order to help define next step options, to focus R&D toward high-leverage areas to analyze and understand the interaction and trade-offs among various components in a fusion device, and to assist the process of concept innovation using an integrated systems approach. These studies are carried out through national teams that utilize the core expertise of the relevant parts of the fusion program. In addition to integrated design studies and assessments, this activity helps to explore and articulate the role of fusion energy in the broader context of the evolving energy marketplace and global climate concerns.

This objective will be accomplished by detailed analysis of fusion devices; incorporating latest understandings from plasma physics and technology research as well as developing new models. An integrated analysis highlights interaction and trade-offs among different areas (e.g., MHD stability and current-drive, edge plasma physics and divertor heat loads) and defines R&D needs to guide present and future experimental and theoretical studies.

Progress will be measured by the creation of state-of-the-art integrated design concepts for both MFE and IFE, by the definition of significant new R&D directions, by the degree of innovation and evolution of fusion concepts toward attractive and practical end-products, and by the incorporation of fusion energy into long-range energy policy and planning.

Description and Key Issues:
The main issues for systems and design activities are the optimization of the tokamak concept, the evaluation of alternative approaches, including magnetic and inertial fusion concepts, the evaluation of socio-economic factors on fusion development and the identification of attractive next step facilities.

Implementation Approaches:
3.4.2.1 Carryout engineering design work and system optimization studies for next step burning plasma devices: Identify and understand key issues that need to be addressed, resolve technical issues and be ready to move forward with participation in a next step burning plasma experiment.

3.4.2.2 Study inertial fusion energy concepts, with particular emphasis on chambers and chamber interfaces with target and driver systems.

3.4.2.3 Study advanced MFE concepts (proof-of-principle or beyond), such as the compact stellarator, to evaluate and improve the attractiveness of these concepts for energy applications.

3.4.2.4 Perform socioeconomic studies in order to better understand the possible roles of fusion in the global energy marketplace and to better represent fusion energy in long-range energy policy and planning.

3.4.3: FUSION (CHAMBER) TECHNOLOGIES

5-Year Objective: Demonstrate the scientific feasibility of innovative plasma chamber technologies for magnetic fusion energy; assess facilities needs for this development, including opportunities for international collaboration.

Research on innovative plasma chamber technologies for magnetic fusion energy concepts is focused on high power density solid and flowing liquid first wall and divertor concepts. Corresponding performance limitations and necessary development programs will be identified. Implications on materials selection and testing, plasma surface interaction, components fabrication and maintenance, tritium management, chamber and divertor design, costing, licensing, safety, and waste disposal will be examined.

Progress will be measured in the chamber area by assessing the compatibility of proposed schemes with plasma performance constraints and projections for achieving high power density handling, high power conversion efficiency, low failure rates, faster maintenance, and simpler technological and material constraints. In the safety and fusion fuels area, it will be measured by the ability to understand and control hazards and by the safety and environmental impact of fusion facilities."

Description and Key Issues:
The main issues for chamber research are (1) determining limits on the amount of material allowed to evaporate and sputter from solid and liquid surfaces based on sophisticated edge modeling coupled to experimental results; (2) establishing hydrodynamic models and exploring various liquid formation schemes in different MFE confinement configurations; (3) evaluating the performance of promising liquid and solid wall concepts; (4) identifying promising high-temperature structural materials; (5) developing technology that can handle and process tritium safely; (6) identifying the hazards of fusion systems and their potential release mechanisms; and (7) developing the analytical tools (e.g., codes, models, etc.) that demonstrate the safety aspects of fusion.

Implementation Approaches:
3.4.3.1 Identify the most promising chamber configurations with respect to different MFE configurations. Explore the possibility of proof-of-performance tests in one or more confinement devices.

3.4.3.2 Compare modeling and test results of the maximum allowable evaporation rate from the liquid surface with respect to different MFE confinement schemes (See also 3.4.1).

3.4.3.3 Obtain experimental data on the achievable minimum liquid surface temperatures without MHD effects for liquid flow under high power density conditions.

3.4.3.4 Identify practical heat transfer enhancement schemes necessary for minimizing liquid surface temperatures and improving solid-wall concepts.

3.4.3.5 Evaluate the performance and reliability of advanced solid and liquid wall concepts.

3.4.3.6 Assess environment and safety needs for promising chamber concepts.

3.4.3.7 Develop the knowledge to handle and process fusion fuel.

3.4.3.8 Assess facilities needs for research and development of chamber technologies.

3.4.4: MATERIALS

5-Year Objective: Advance the materials science base for the development of innovative materials and fabrication methods that will enable improved performance, enhanced safety, and reduced overall fusion system costs so as to permit fusion to reach its full potential; assess facilities needs for this development, including opportunities for international collaboration; support materials research needs for existing and near-term devices.

Based on design studies and systems analyses, three candidate structural materials systems which offer a potential for high performance with favorable safety, radioactive waste disposal ratings, and a possibility for recycle have been identified. These materials systems, which are the focus of the current materials research program are (1) advanced ferritic steels, (2) vanadium alloys, and (3) SiC/SiC composites. Copper alloys are also considered for special heat sink applications. Significant progress has been made on the characterization and understanding of the properties and performance limits associated with materials processing, fabrication and joining, physical and mechanical properties, chemical compatibility, and effects of irradiation on properties of these three materials systems.

Progress will be measured by assessments of the performance limits of the various materials systems relative to projected operating conditions of high energy neutron fluxes, high surface heat fluxes, chemical compatibility in the fusion environment, and potential operating lifetime.

Description and Key Issues:
The main issues for materials research are the implementation of a fully integrated theory-modeling-experimental program (how to routinely incorporate recent materials science advances into the fusion materials program) and the development of adequate fusion materials test facilities (intense neutron source, etc.).

Implementation Approaches:
3.4.4.1 For ferritic steels, establish acceptability of ferromagnetic materials in MFE power plants; establish the magnitude of combined effects of radiation hardening and helium generation on fracture behavior; and explore nanotechnology concepts such as oxide dispersion strengthening as a means of improving high-temperature strength and expanding upper operation temperature limits.

3.4.4.2 For vanadium alloys, develop a self-healing, insulator coating to mitigate magneto-hydrodynamic effects for lithium-cooled systems; define the operating window for vanadium alloys including effects of high helium concentrations with neutron damage and chemical compatibility; and develop fabrication/welding methods applicable to large fusion systems.

3.4.4.3 For silicon carbide composites, develop composites with advanced fibers and interphase structures with improved radiation damage resistance; establish the effects of radiation on the thermal conductivity and the level of allowable heat fluxes; and develop joining and sealing technologies.

3.4.4.4 Reduce the overall cost and schedule for development of fusion materials by heavy utilization of state-of-the-art materials science theory and modeling analyses (coupled with appropriate focused experiments on model systems) on key cross-cutting feasibility issues such as radiation-induced mechanical property degradation, development of coatings, etc.

3.4.4.5 Identify new facilities (point and/or volume neutron sources) required for materials development and component testing.

3.5 IFE Goal 1: Advance the fundamental understanding and predictability of high energy density (HED) plasmas for IFE, leveraging from the ICF target physics work sponsored by the National Nuclear Security Agency's Office of Defense Programs.

How do limits on driver intensity and target requirements for irradiation symmetry, hydrodynamic instability, pulse shaping, and fusion ignition impact the gain achievable in inertial fusion targets?

A primary goal for IFE is to develop a quantitative understanding of HED plasmas sufficient to specify tradeoffs among target fabrication, driver requirements, and chamber characteristics, for targets with a product of driver efficiency η times target gain G adequate for economical production of energy (generally requires $\eta G \sim 10$ or more but values of 7 or less may be acceptable if driver and chamber costs are sufficiently low.) A secondary goal is to identify and exploit synergism between the HED physics developed for IFE and that of importance in other fields including astrophysics and planetary physics.

Much of the HED physics for IFE is drawn from the large U.S. research program in National Nuclear Security Agency's Office of Defense Programs' (DP) Inertial Confinement Fusion (ICF) Program, and the key issues for inertial fusion ignition and propagating burn will be tested in the National Ignition Facility (NIF) in the medium term (8 to 10 years). However, IFE target requirements generally go beyond those needed for DP-ICF, such as higher gain for low recirculating power as well as targets that can be mass-manufactured at low cost, injected at high pulse rates, and are compatible with rep-rated IFE drivers. In the near term (next five years), the OFES-sponsored IFE target physics under IFE Goal 1 will concentrate on these IFE-specific needs, using extended and improved computer models to study IFE target designs, and through selected target experiments on existing DP and international laser and pulsed-power facilities.

Common Implementation Approaches for all IFE Goal-1 Objectives:
The following five (five-year) objectives described below address different major scientific issues in IFE target designs and describe connections to other areas of HED physics. All objectives use a similar implementation approach, applying numerical computer models (in some cases modified as needed for IFE) and experimental target physics data developed in the National Nuclear Security Agency's Office of Defense Programs' (DP) ICF Program to specific IFE target issues. For features that are unique to IFE targets, it may be possible to carry out experiments on existing and planned DP facilities. Some advanced targets such as those being examined for fast ignition will require experimental validation on existing or planned DP or international facilities.

3.5.1: BEAM TARGET INTERACTION AND COUPLING

5-Year Objective: Advance the understanding of driver interaction and coupling in IFE targets to a level sufficient to determine tradeoffs among driver beam focusing, absorption, x-ray production, beam-plasma instability, and target preheat.

Progress will be measured by integrated IFE target designs that have adequate gain for each combination of driver, chamber and target, subject to the DP-ICF target physics database on absorption and x-ray conversion efficiency of laser light at various wavelengths, and data on heavy-ion ranges in plasma targets from accelerator facilities.

Description and Key Issues:
Reduced coupling efficiency and adverse effects from laser-plasma interaction limit conventional laser-driven hot spot ignition targets to I ~10^{15} W/cm^2. For ion-driven targets, beam emittance affects the achievable spot size, and ion target designs which accommodate this require ion beam intensities I~ 10^{14} to 10^{15} W/cm^2. In direct-drive, the driver beams are aimed directly at the fusion capsule. In indirect drive, the driver energy is absorbed and converted to x-rays by material inside the hohlraum that surrounds the fusion capsule. For pulsed power driven z-pinches, the driver energy is coupled electrically to a z-pinch load and converted to x-rays upon stagnation. Key issues for the z-pinch IFE concept include reproducibility of x-ray production upon stagnation with a pulse-shaping target and transport of z-pinch x-rays into a hohlraum. In a more speculative fast ignition approach, the fuel is compressed to high density without a hot spot and then a separate beam with intensities of 10^{19} to10^{20}W/ cm^2 is used to ignite a region on the surface of the compressed fuel. Either lasers or ion beams might provide fast ignition in principle, but the required intensities are more easily reached with available lasers, to provide needed data to test the models.

In conventional inertial fusion targets, collisional effects are predominantly responsible for absorption of the driver energy. However, plasma collective effects in the target plasma, particularly for lasers, affect both the absorption and the distribution of electrons. Instabilities such Raman scattering, resonance absorption, and the two-plasmon decay instability can generate electrons sufficiently energetic to cause target preheat and reduced compression. Levels less than 1% can adversely affect direct drive laser targets while levels of 5-10% will affect indirect-drive targets. Because indirect-drive laser targets have a larger volume of plasma and a longer beam pathlength through that plasma, these plasma instabilities have in practice been a greater problem for indirect drive targets than for direct drive targets. However, for both types of targets, the adverse effects of plasma instabilities have been the dominant source of limitations on laser intensity and the principal reason that conventional laser driven targets utilize lasers with wavelengths of 1/2 micron or less.

For lasers that have an output longer than about 0.5 micron, techniques must be employed to convert the laser wavelength to a higher frequency. The choice of laser wavelength can also significantly affect the final optics approaches in the fusion chamber. Shorter laser wavelengths have better coupling efficiency but more difficult optical materials problems for damage. For ion beams, because of differences in the stopping power of bound and free electrons, uncertainty in the charge state of target ions and beams ions can result in uncertainty in the ion range. In the fast ignition approach to laser-driven targets, the coupling is entirely by plasma collective phenomena. Understanding the issues of absorption and transport for fast ignition is at a very early stage. For all approaches to indirect drive, the high-z hohlraum wall confines the radiation and is the dominant source of x-ray loss. Although the hohlraum wall is typically near LTE, the opacity of high-z materials is quite complex and is the subject of active research. In order to validate calculations for ion beam targets, some additional experimental tests of ion beam deposition and radiation production are required. The choice of materials for the capsule (and hohlraum in the case of indirect drive) affects the safety and environmental characteristics of a fusion power plant.

3.5.2: ENERGY TRANSPORT AND SYMMETRY

5-Year Objective: Advance the understanding of energy transport to a level sufficient to determine the tradeoffs between the number of beams and chamber geometry, beam spatial profile, beam pointing accuracy and beam power balance, as well as hohlraum geometry for indirect drive.

Progress will be measured by integrated IFE target designs that have adequate gain for each combination of driver, chamber and target, subject to the DP-ICF target physics database on convergence ratios and driver beam symmetry, and on data for x-ray transport and smoothing in hohlraums.

Description and Key Issues:

In hot spot ignition targets, the convergence ratio C_r, defined as the ratio of the initial outer radius of the ablator to the final compressed radius of the hot spot, range from 20-40, depending on the implosion pressure and implosion velocity. An asymmetric implosion results in enhanced thermal conduction from the hot spot to the cold surrounding fuel, and a reduced conversion of the available kinetic energy into compression and heating of the fuel. Thirty-two to 60 or more beams are typically utilized in direct drive designs. Individual beams are usually focused to completely cover the initial diameter of the capsule. However, some schemes propose refocusing, i.e., zooming, of the laser beams during the implosion for improved coupling efficiency to the capsule as it implodes. For indirect drive, hohlraum geometry, beam placement, and internal structure in the hohlraum contribute to symmetry of radiation flux on a capsule.

The key issues for symmetry for direct drive depends on the number of beams, the beam spatial profile, the beam pointing accuracy, and the beam power balance. Current estimates indicate hohlraum targets can tolerate about 200 micron pointing errors without a reduction in gain. Direct drive targets may require beam pointing accuracy and target injection accuracy of about 25 microns. In principle, it is possible to develop non-spherical beam illumination geometry for direct drive. This requires non-symmetric intensity profiles in the beams (or non-spherical targets) and an improved understanding of the target plasma profiles. For indirect-drive, symmetry is dependent on detailed knowledge of high-z opacity, radiation transport, and motion of hohlraum surfaces. For the z-pinch IFE concept, key issues include x-ray transport and symmetrization within the hohlraum.

Because of conversion of driver energy to X-rays and transport to the fuel capsule, hohlraum targets are in general less efficient than direct-drive targets. More efficient laser driven hohlraums, or more efficient lasers, must be developed before it will be possible to do indirect drive with lasers for IFE.

In order to validate calculations for ion beam targets, some experimental tests of unique hohlraum features are needed beyond those which will be carried out by the DP ICF Program. The driver beam geometry and target configurations impact the options available for the fusion chamber design. Chamber designs for neutronically thick liquid walls lend themselves easily to targets (e.g. indirect-drive with ion beams) that can accept driver beams limited to a narrow range of directions. Direct drive targets require spherically-distributed ports in the chamber wall, hence dry-wall chambers are the prime candidate for this approach. Direct drive targets may be easier to fabricate because they are simpler, but may be harder to inject into the chamber than indirect drive targets with hohlraums acting as a thermal barrier to keep the target cold. Requirements for target injection and tracking appear more tractable for indirect drive targets than for direct-drive targets.

Radiation flow is a fundamental component of astrophysical phenomena. For example, modifications to transport due to expansion are critical for predicting the emission history of a supernova explosion. It is possible to do scaled experiments, relevant to astrophysical phenomena, in ICF facilities. Radiation transport is also important in the radiation hydrodynamic evolution of astrophysical jets.

3.5.3: IMPLOSION DYNAMICS AND EQUATION OF STATE (EOS) OF MATERIALS

5-Year Objective: Advance the understanding of implosion dynamics and EOS of fusion materials to a level sufficient to determine the pulse shape and timing requirements for IFE targets.

Progress will be measured by integrated IFE target designs that have adequate gain for each combination of driver, chamber and target, subject to the DP-ICF target physics database on capsule EOS, opacities, and pulse shape (shock timings).

Description and Key Issues:

In direct-drive, the driver beam energy is directly deposited in the fusion capsule and the pressure is generated by electron conduction that drives the shell ablation. In laser-driven targets, laser–plasma interaction effects limit the incident flux to ~10^{15} W/cm^2. In indirect-drive, the driver beam energy is deposited in an x-ray converter and x-ray transport to the fusion capsule drives the ablation process. In ion beam–driven targets, the pressure may be limited by the focused intensity achievable, and so ion target designs aim to minimize the ablation pressure. Precise and flexible pulse shaping of the driver beam power is required. To achieve the required hot spot and cold main fuel densities with minimal energy, the cold fuel must remain nearly Fermi degenerate. This pulse shaping involves a series of precisely timed shocks that propagate in sequence through the fuel shell. In general, the magnitude and timing of these shocks depends on the EOS of the materials in the fusion capsule. The timing of successive shocks must be known to about 100 ps. In addition to accurate pulse shaping, the target gain can be enhanced by heating the ablator to a higher adiabat, and hence make it more resistant to instability, while keeping the fuel on a lower adiabat to maximize density and, hence gain. Achieving the level of control required for both proper shock timing and for controlling the adiabat of the ablator involves a combination of accurate knowledge of the EOS and experimental iteration. Existing lasers and z-pinch x-ray sources can be used near term for accurate measurement of EOS and shock timing in target materials.

In laser direct-drive targets, the ablation process depends on electron conduction from the low-density corona (density < $10^{21}/\lambda^2/\text{cm}^3$ with λ in microns) to the ablation front (density ~$10^{24}/\text{cm}^3$). This calculation typically uses Spitzer conductivity and a diffusion approximation. This approximation breaks down at typical laser fusion intensities as the laser wavelength approaches one micron. For the intensities involved in fast ignition, no adequate description of energy transport is currently available. In indirect drive, the ablation pressure for a given x-ray flux depends on the capsule albedo. This requires an accurate knowledge of the opacity of ablator materials. Recent experiments have shown that hydrogen is nearly a factor of 2 more compressible in the 1 Mbar pressure range than previously expected. There are likely to be similar levels of uncertainly in other materials used in inertial fusion capsules. Capsule designs for IFE must be robust to uncertainty in the EOS of this magnitude. To obtain an accurate predictive capability for shock timing and pulse shape requirements, EOS experiments on materials unique to IFE targets need to be done. The ability to perform accurate pulse shaping directly affects the target gain and the driver efficiency as well as the driver size required for energy production.

There is an important synergism between the EOS of ICF targets and that of materials in the giant gas planets. The internal structure of these planets is very sensitive to the EOS of hydrogen and helium. The DP ICF facilities and future IFE facilities have unique capabilities for exploring materials in the multimegabar regime under conditions in which the materials remain degenerate.

3.5.4: HYDRODYNAMIC INSTABILITY AND MIX

5-Year Objective: Advance the understanding of hydrodynamic instability and mix sufficient to determine the tradeoffs between techniques to optimize ablation stabilization as well as other approaches to reducing instability growth, and the driver requirements on intensity, spatial uniformity and pulse shaping.

Progress will be measured by integrated IFE target designs that have adequate gain for each combination of driver, chamber and target, subject to the DP-ICF target physics database on hydrodynamic stability and mix.

Description and Key Issues:

The work that can be done on the imploding fuel of an ICF capsule is the product of the pressure generated by the ablation process times the volume enclosed by the shell. Hence, for a given pressure, a larger thinner shell that encloses more volume can be accelerated to a higher velocity than can a thicker shell of the same mass. The peak achievable implosion velocity determines the minimum energy (and mass) required for ignition of the fusion fuel in the shell. Hydrodynamic instabilities impose an upper limit on the ratio of the shell radius R as it implodes to its thickness ΔR. This limit results in a minimum pressure or

absorbed driver irradiance and also results in maximum acceptable levels of capsule roughness and small spatial scale driver irradiation non-uniformity. Hot spot ignition targets require control of room temperature growth to 5-7 e-foldings for capsule surface finishes of 1000-100 Å and precise control of driver beam uniformity. Targets that de-couple the compression and ignition steps by utilizing fast ignition may be able to tolerate 1-2 more e-foldings of growth and hence allow up to an order of magnitude greater initial surface roughness. For larger capsule sizes, such as considered for z-pinch IFE, a key issue to explore is whether the yield sensitivity to instability growth might be reduced with larger capsules.

The main issue for hydrodynamic instabilities is optimization of ablation stabilization techniques, which reduce instability growth, while achieving adequate target gain. Optimization involves the driver intensity and laser spatial uniformity in direct drive, x-ray intensity in indirect drive, the energy deposition profiles, x-ray and electron preheat and pulse-shaping, and target material equation-of-state properties. For direct drive targets, the smoother the laser beam, the lower the effective perturbation amplitudes imprinted by the beam itself on the target. The amount of growth that is tolerable depends not only on the laser smoothness, but on the surface finish and homogeneity of the targets as well, although it is generally thought that the targets can be made smoother than the laser. In order to validate calculations for some ion beam targets in which the fuel capsule is embedded in a low density foam, experimental tests of radiation-driven, room temperature instability are needed beyond those which will be carried out by the DP ICF Program.

For ion beams, higher intensity beams require smaller spots and shorter pulses with more extreme pulse shaping that increase the scientific challenge for the drivers and impacts the driver architecture. For pulsed-power driven z-pinches, instabilities in the z-pinch implosion can affect the x-ray intensity. The choice of capsule material along with the surface finish and homogeneity requirement strongly affect the feasibility of developing low-cost fabrication techniques. The choice of materials for the capsule (and hohlraum in the case of indirect drive) affect the safety and environmental characteristics of a fusion power plant. The choice of capsule materials and capsule structure chosen to control instabilities can affect the feasibility of injection into the fusion chamber, particularly for direct drive targets.

Many phenomena in astrophysics are sensitive to the development of hydrodynamic instabilities in compressible media. For example, a core collapse supernova, which occurs when the iron core of a massive star collapses, is very sensitive to mixing of the core into the surrounding envelope. It is possible to do scaled experiments of relevance to this phenomena on ICF facilities.

3.5.5: IGNITION AND BURN PROPAGATION

5-Year Objective: Advance the integrated understanding of coupling, symmetry, pulse shaping, and instability sufficient to specify the optimal assembly of fuel for ignition and burn propagation subject to tradeoffs in driver, chamber and target fabrication specifications.

Progress will be measured by integrated IFE target designs that have adequate gain for each combination of driver, chamber and target, subject to the DP-ICF target physics database on beam coupling, energy transport, symmetry, EOS, hydrodynamic stability and mix.

Description and Key Issues:
All high gain IFE targets rely on hot spot ignition followed by propagation of the burn via alpha deposition and electron conduction into the surrounding cold fuel. The compression achievable in a spherical implosion and the ignition threshold depends strongly on the implosion velocity v_{imp}. For a fixed peak driving pressure and fuel entropy, if the pulse shape can maintain compressibility independent of v_{imp}, the ignition threshold varies as v_{imp}^{-n}, where $n \approx$ 5-6. For capsules in which the implosion pressure

increases as ν_{imp} increases, the ignition threshold is an even stronger function of velocity. Once the hot central region of the fuel reaches 10 keV with a ρr equal to the range of the alpha particles (~0.3 g/cm2 at 10 keV), the burn will propagate into, and ignite an indefinite amount of surrounding cold fuel. The presence of a self-sustaining burn wave defines ignition in inertial fusion. These ignition and burn propagation conditions are predicted to be nearly independent of fuel mass over a wide range of sizes. Thus, a demonstration of ignition and burn on the NIF or other facility will determine the requirements for high gain with a larger IFE driver.

The assembly of the hot spot is largely determined by a balance between work done by the cold fuel shell on the hot spot during compression and electron conduction loss from the hot spot into the surrounding cold fuel. The conduction loss is determined both by the thermal conductivity and by the interface surface area that is affected by asymmetry and hydrodynamic instabilities. The work is also affected by deviations from spherical symmetry of the imploding shell. Burn propagation is affected about equally by alpha particle deposition and by electron conduction from the hot fuel to the cold fuel. The physics of electron conduction is studied in sub-ignition hot spot targets in existing laser facilities and the DOE DP has a large experience base burning DT in much larger size devices. However, NIF is currently expected to provide the first demonstration of ignition and propagating burn using a laboratory scale driver. Because lower fuel density is required, more fuel can be compressed for a given amount of energy in the fast ignition approach than in the central hot spot ignition approach. If the fuel can be ignited with reasonable efficiency, higher gains and smaller driver requirements would result. A variety of drivers can be considered to compress the fuel for fast ignition, including lasers, heavy-ions, and z-pinches.

Tradeoffs among all the effects which determine fuel assembly, ignition, and burn propagation will impact driver feasibility and driver cost as well as target fabrication approaches and chamber design. If target gain is sufficient with small drivers, the rep rates must be high, the targets cheap, and chamber designs must be capable of quickly reestablishing conditions adequate for target injection and driver propagation. If large capsules are required to achieve adequate gain, the driver must be cheap and the chamber must be capable of accepting larger yields.

3.6 IFE Goal 2: Develop the science and technology of attractive rep-rated IFE power systems leveraging from the work in the DP ICF Program.

The knowledge base to be obtained by IFE research over the next five years in the Proof of Principle (PoP) phase must provide the science and technology basis for the next step, called an Integrated Research Experiment (IRE). In the IFE strategy, the IRE, together with supporting technology R&D, and confidence in target physics performance on the NIF and other ICF facilities, provide the basis for a decision to proceed to the Fusion Energy Development stage called an Engineering Test Facility (ETF). To support this IFE development strategy, an IRE would test many non-nuclear scientific and technical issues for an IFE approach, including a prototypical driver beam or bundle-of beams at rep-rate, beam transport to a test chamber, and final focus to a target in a representative chamber environment. With beam energy between 3 and 30 kJ, an IRE would not test nuclear effects. In addition to driver and focusing-related experiments, PoP research must address basic feasibility issues of chamber clearing, lifetime, and safety, and of methods for low cost target fabrication and injection.

3.6.1: HEAVY ION BEAM EXPERIMENTS AND SUPPORTING ACCELERATOR TECHNOLOGIES

5-Year Objective: Perform single-beam, high-current experiments to validate ion production, acceleration, and transport in a driver-relevant regime (line charge 10-100 times higher than in present experiments). Develop technologies to minimize the cost of these experiments and the IRE.

Performance will be measured by the achievement of beam quality at sufficient currents, and by sufficient improvements in enabling accelerator technology, to support the basis for an ion beam IRE. The following are the near-term metrics for the HIF approach:

- Beam brightness, in a single-beam high current transport experiment, that meets or exceeds driver requirements at 0.5 to 1 ampere with a beam particle energy of 1 to 10 MeV and ~100 quadrupoles.

- Development of a compact injector that can supply 0.5 to several amperes per beam in a multi-beam array.

- Technology improvement to enable an IRE, including quadrupole arrays costing $\leq$ \$10/kA-m, insulators at ~ \$0.01/V, energy storage at \$3-10/J, switches at \$$10^{-5}$/W, and magnetic cores at \$5–10/kg.

- Component lifetimes allowing 10^9–10^{10} shots, and with integrated core and pulser efficiencies that extrapolate to > 20% overall efficiency for a driver.

Description and Key Issues:

Ion sources and injectors must be developed which meet requirements of brightness, uniformity, longevity, current, and cost. Currently a 2 MV injector has been built with adequate brightness and current, and with marginal longevity, but it may be too large to be used as a unit of an economical multiple-beam injector. Intense ion beams -- non-neutral plasmas -- must be accelerated to several GeV with the required brightness and pulse shape for a driver. A quantitative understanding of beam emittance growth, halo formation, entrainment of stray electrons, and inductive-wall instability is necessary so that a fusion driver can operate at a high line charge density, acceleration rate, beam pipe filling factor, and efficiency. So far, small scaled experiments with a few milliampere beam currents have shown low emittance growth for ~ 100 lattice periods at relevant beam tune depression and perveance, but these experiments need to be done at driver-scale line charge densities and at higher quadrupole aperture fill factors to provide more relevant tests of entrainment of electrons and halo losses. Enabling and affordable technology is essential for an IRE, which must settle scientific issues for HIF in an integrated way.

Implementation Approaches:

3.6.1.1 <u>Research on ion sources and injectors</u>: Surface ionization sources that produce alkali metal ions are currently the workhorse of the program. Although one could base an IRE or fusion driver on these sources, they have a number of limitations. They are limited to only a few of the alkali metals and they are relatively inefficient in terms of power consumption. They are also large. Smaller size would be desirable to reduce cost. Consequently, the development of more compact ion sources is an important part of the next several years of research. If this research is successful, it will lead to a less expensive research program and to a less expensive full-scale driver. The potential benefit is large for a small investment.

3.6.1.2 <u>High current (1-ampere beam) transport experiments</u>: As noted above, earlier experiments have had beam currents (or line charge densities) that were an order of magnitude (or more) smaller than those needed in a full-scale driver near the low energy end of the accelerator. The high-current experiment will be a single-beam transport experiment using electrostatic and magnetic quadrupoles. The number of quadrupoles will be ~100 in order to be sensitive to possible long-term emittance growth and halo formation. This experiment will be the first transport experiment with driver-scale beams and it will address important issues related to the preservation of good beam quality (focusability), halo production, beam sensing and alignment, and beam size. The high-current experiment is needed to provide a sound basis for building an IRE.

3.6.1.3 <u>The low-cost enabling technologies</u> needed for the research program (IRE) and drivers are (1) low cost, low loss magnetic core material for induction acceleration, (2) high-vacuum-compatible inorganic insulators that can be fabricated in meter-diameter size with cast-in flanges, (3) compact, high field arrays of superconducting quadrupole magnets for transporting multiple beams in an induction linac, and (4) efficient, low cost, rep-rated high voltage pulsers to drive the induction cores. Working with potential vendors is important to improve the manufacturing consistency, performance and cost of each technology. The superconducting magnet R&D can make use of expertise in the MFE Program.

3.6.2: INTEGRATED ION BEAM MODELING, FOCUSING AND TRANSPORT

What are the limits to charged particle beam transport and focal intensities in the beam current regimes of interest to IFE?

5-Year Objective: Complete detailed and end-to-end (ion source-to-target) numerical simulations of the IRE and full-scale drivers, including focusing and chamber transport, and compare model prediction with experiments in heavy-ion beam accelerations, drift compression, focusing and chamber transport.

Performance will be measured by

- Driver simulations, from tested and bench-marked integrated numerical models, giving consistent end-to-end beam descriptions in 3D.

- Experimental and theoretical evaluation of neutralized ballistic chamber focusing mode, in 2-D and with multiple beam effects, that meet driver requirements and which provides the physics basis for IRE focusing experiments.

- An integrated target design consistent with accelerator capabilities, in 2-D or 3D as appropriate, for indirect drive, with $\eta G > 10$, and which is compatible with an IFE power plant system.

Description and Key Issues:

The detailed beam dynamics in the accelerator must be consistent with beam requirements for injection on the front end, and with requirements for beam pulse compression, final focusing, and chamber transport, and target requirements on the back end. Since a full-scale accelerator will not be constructed before the Engineering Test Facility for IFE, a means to confidently predict the performance of such a machine from fully-tested and bench-marked integrated numerical models is necessary. The beam experiments 3.6.1.1 and 3.6.1.2 will test key parts of the integrated models, and later in the next phase, the IRE will provide a more complete test.

Heavy ion beams must be focused and transported through the fusion chamber onto the target, in the presence of beam stripping, neutralization, background ionization, and other processes. Beam-plasma interaction experiments are required to check the physics of simulations to predict beam space-charge reduction and stripping in the presence of plasmas. There will be limits on both beam dimensionless perveance (perveance is the ratio of the beam space charge potential to the ion kinetic energy, or equivalently, the inverse square of the distance a beam will travel without additional focusing before expanding by its diameter) for final focusing, and on the absolute line charge density and beam space charge potential set by electrical breakdown on the pipe wall after peak longitudinal beam compression before final focus. These Phase I experiments are needed for an IRE, which will be an integrated experiment including beam acceleration, drift compression, final focusing and chamber material interactions.

Implementation Approaches:

3.6.2.1 3-D particle-in-cell, Vlasov, and delta-f codes are applied to model self-consistent IRE and driver beam dynamics, halos, potential beam-accelerator coupling and instabilities, misalignment effects and emittance growth, with end-to-end analytical and numerical modeling of fusion accelerators. Other 2-D and 3-D particle-in-cell and hybrid particle-in-cell/fluid models of chamber transport and beam neutralization take the incident beam distributions from the accelerator and model the subsequent focusing of beams in the IRE experiment and on targets in power-plant designs. Effects of ion stripping and ionization of gas from target-emitted photons are included.

3.6.2.2 The primary approach to beam focusing to be studied is ballistic focusing with plasma neutralization of the beam space charge. Previous experiments have demonstrated beam focusing and space charge neutralization at the few hundred-microampere level, where the beam space charge potential before neutralization is a few volts. Experiments are needed to study plasma neutralization of beam space charge at higher currents, (e.g. of the order of an ampere using existing MeV injector beams), where the space-charge potentials before neutralization are a few keV. A higher beam space charge potential will allow better measurements of the electron heating due to neutralization of the beam electrostatic energy, which affects the subsequent compressibility of the neutralizing electrons as the ions focus towards the target, as well as the measurement of nonlinearities in the residual radial electric fields that can cause effective emittance growth in a converging beam. These measurements will test the physics models for electron dynamics in particle-in-cell codes used to model plasma neutralization of focusing beams for the IRE and for power plant chamber designs.

3.6.2.3 Key issues of advanced focusing and chamber transport need further modeling and exploration, including discharge channel propagation, and self-pinched propagation.

3.6.2.4 Better measurements of stripping of fast heavy-ions at moderate charge state are needed to benchmark and improve present theoretical models. Stripping of heavy-ions on chamber gas and background plasma can increase the effect of residual electric fields deflecting beam ions from the edge regions of incompletely neutralized beams. Experiments on existing heavy-ion accelerators for nuclear research, such as at GSI in Germany, can be used to test the various atomic physics models.

3.6.3: KRF LASER DRIVER EXPERIMENT

5-Year Objective: Build and test a >400-700 joule Krypton-Fluoride laser experiment capable of >6% wall plug efficiency, a single-beam nonuniformity <1%, at 5 Hz pulse-rate for $>10^5$ shots, in a laser architecture that extrapolates to < $400/joule for a power plant driver. Perform additional KrF development required for a KrF IRE decision: carry out related physics studies to improve direct-drive target design, advanced front end for pulse shaping and zooming, improved optics coating for high damage threshold mirrors, and systems analysis.

Performance will be measured by the adequacy of the results of the laser experiments and modeling to enable a laser-driven IRE for the medium term IFE objectives. The following are the near-term metrics for the KrF approach:

- An overall efficiency demonstrated in a KrF laser experiment of >6-7%.
- A durability demonstrated in a KrF laser experiment $>10^5$ shots between maintenance.
- An optics damage threshold of 5 J/cm^2 .
- A cost study that shows that extrapolation of the PoP laser experiment to a driver would meet $225/J at driver scale.
- A KrF laser uniformity on target with better than 2 THz bandwidth, and a 0.2% beam uniformity in high mode numbers.
- An integrated direct-drive target design for KrF, in 2D or 3D as appropriate, with $\eta G > 7$, and compatible with an IFE power plant system.

Description and Key Issues:

A KrF laser must achieve the efficiency, beam brightness, and durability required for direct-drive target designs that have adequate gain for a power plant. KrF development in the PoP phase must address the key issues for a KrF driven IRE. Here, a KrF IRE is envisioned to be an integrated repetitive demonstration that a power plant sized laser can be steered to illuminate a target injected into a reactor chamber environment, and it can do so with the uniformity and precision required for inertial fusion energy. The “power plant sized” laser will provide the energy, pulse shape control, wall plug efficiency, and target illumination uniformity required for a single beam line of a laser fusion power plant. The energy of the beam line will likely be in the range of 50 to 150 kJ, and a fusion power plant will require 20 to 50 identical beam lines. The chamber will have the same type of environment (e.g. gas needed for x-ray shielding, grazing incidence final optics, etc) as envisioned for a power plant.

Improvements in the intrinsic KrF laser efficiency, which may be possible with various gas mixtures or excitation methods, need to be explored. A higher efficiency driver can relax target gain requirements. Improvements in direct-drive target design, such as a zoom-focus capability, would relax the efficiency required for an IFE power plant KrF driver. Improvements in the efficiency, durability and cost of pulsed power must be achieved.

Implementation Approaches:

3.6.3.1 A new electron-beam pumped KrF laser experiment is needed with an aperture of 30 x 30 cm^2 that will produce more than 400 Joules per pulse at 5 Hz. The goal is to demonstrate a mean time between failure of more than 10^5 shots, the feasibility of achieving a wall plug efficiency of more than 6%; and to develop the associated laser technologies that would extrapolate in larger lasers with a capital cost of less than $400 per Joule. The KrF laser experiment must be large enough to test most of the technologies of a fusion-size electron-beam pumped KrF amplifier, while still being small enough to easily make modifications.

3.6.3.2 A KrF physics program is needed to develop improved codes to model the basic KrF laser behavior, and compare with experimental data using existing KrF lasers. Improved direct-drive target designs and hydrostability/imprint analysis using 3-D implosion codes are needed. An advanced front-end program is needed to develop a new oscillator and preamplifier that can tailor the laser pulse to produce the necessary temporal shaping, spatial profiles, and zooming. An advanced coating/optics program is needed to enhance the durability of the optical components, by developing fluorine/UV resistant coatings for the amplifier windows, along with higher damage threshold mirrors. A KrF systems analysis is needed to design an economically feasible 2 MJ KrF laser for a power plant, by integrating the laser architecture with other systems, and establishing the costs of the facility and of operations/maintenance.

3.6.4: DPSSL LASER DRIVER EXPERIMENT

5-Year Objective: Build and test a >100 joule Diode Pumped Solid State Laser (DPSSL) experiment capable of >10% wall plug efficiency at the 1.047 micron (1 ω) wavelength, a beam nonuniformity on target < 0.1 to 1%, at 10 Hz pulse-rates for $>10^8$ shots, in a laser architecture that extrapolates to < $400/joule for a power plant driver. Perform supporting DPSSL research needed in addition to a DPSSL experiment: lower cost diodes, improved DPSSL IFE target designs, improved crystal growth, and system integration and scaling.

Performance will be measured by the adequacy of the results of the laser experiments and modeling to enable a laser-driven IRE for the medium term IFE objectives. The following are the near-term metrics for the DPSSL approach:

- An overall efficiency in a laser experiment of 10% at 1ω.
- A diode efficiency of 55 %, and cost of $ 0.5/Wpeak.
- A beam non-uniformity of 0.1 to 1 % on target.
- An overall mean # of shots between maintenance $> 10^8$.
- A frequency conversion efficiency to 3ω of 80% with 0.3 THz bandwidth for crystals, or 1-2 THz bandwidth with glass.
- A crystal size of 15 cm.
- An integrated target design, in 2D or 3D as appropriate, for direct drive or indirect drive, sufficient for a power plant, with $\eta G > 10$, and compatible with an IFE power plant system.

Description and Key Issues:
A DPSSL laser must achieve the efficiency with beam bandwidth/smoothness required for current direct-drive target designs that have adequate gain for a power plant, at an economic cost. DPSSL drivers share many laser physics and design features with the National Ignition Facility including optical pumping, energy storage, multi-pass amplification, single-pulse energy extraction, temporal pulse shaping, linear and nonlinear wave-front distortions, frequency conversion, and beam smoothing. The development of DPSSLs for IFE must address the remaining challenges including enhanced efficiency, higher repetition rate, long lifetime, optimized laser beam-smoothness, and reduced capital cost. The DPSSL PoP developments will provide the basis for proceeding to the next step, a DPSSL IRE, and evaluate whether this technology will ultimately meet the needs of IFE. A DPSSL IRE would be used as an IFE chamber technology research tool potentially including an average power neutron source using high intensity laser pulses.

Increasing crystal bandwidth to improve beam smoothness comes at the expense of optical storage time, and decreasing optical storage time either increases peak diode pump power and cost, or degrades pumping efficiency, or both. Improvements in DPSSL crystal bandwidth would improve beam smoothing and increased optical storage time at the same time would reduce diode cost. The ability to grow crystals of the size required for full scale DPSSL beamline must be demonstrated. Fully integrated calculations of direct drive targets with gain adequate for a DPSSL laser are required. Improvements in indirect-drive laser target design would be required for an IFE power plant, with achievable DPSSL efficiency, to be compatible with existing protected wall chambers.

Implementation Approaches:
3.6.4.1 An integrated DPSSL laser experiment is needed with a capability of achieving 10% efficiency at 1ω, 10 Hz repetition rate, at a 2-5 ns pulse width, with energies of 100 J at the 1.047 micron (1ω) wavelength. After initial operation at the first harmonic, the experiment should be upgraded to provide average power third-harmonic frequency conversion with ultra-smooth laser beams.

3.6.4.2 In addition to the 100 J DPSSL experiment, there needs to be research to reduce the cost of diodes, improve the crystal growth, determine how to integrate the beamlets into beamlines, and study the system scaling issues. A DPSSL IRE would need to incorporate a "bundle" of several kJ-class full-size beamlets (presently conceived to be 10x15 cm^2 aperture). Improved direct and indirect-drive IFE targets for DPSSLs can have a large potential impact on DPSSL laser driver cost while also increasing the flexibility for simpler chambers with two-sided beam illumination.

3.6.5: IFE CHAMBER AND TARGET RESEARCH

5-Year Objective: Demonstrate feasibility of chamber clearing for thick-liquid-wall chambers, dry-wall chamber concepts that are tolerant of uncertainties in response of materials to fusion pulse and radiation damage, plausible designs for protecting final focusing elements for ion accelerator and laser drivers. Evaluate safety and environmental aspects of IFE power plants and modify designs such that plants can meet the no-public-evacuation safety criteria. Identify credible pathways to low-cost target fabrication, accurate injection, and target survival through experiments and analyses.

Performance will be measured by a knowledge base sufficient for:
(a) predicting liquid chamber clearing rates through tests and numerical simulations of properly scaled model liquid experiments, including simulated target blast forces;
(b) predicting dry-chamber lifetime from:

- Reassessment of carbon composite first wall lifetime (neutron irradiation data)
- Integrated debris calculations to determine target debris
- Evaluation of need for and type of wall protection methods (e.g. chamber gas fill)
- Measurement of erosion rates from granular solid coolants
- Design of rapid first wall change-out procedures;

(c) design of a final-focus/chamber interface design for heavy-ion driven IFE with predicted lifetime much greater than 1 full power year, through self-consistent magnet/chamber designs that simultaneously accommodate the size of final focus magnets, shielding, and the necessary placement to hit a ~ 3 mm radius spot; for laser driven IFE with predicted lifetimes > 1 full power year, through experiments which

- Extend hot-fused silica neutron irradiation data for DPSSLs
- Test GIMM and GILMM mirrors with KrF lasers
- Measure shock effects from anticipated fireballs and propose solutions
- Test effectiveness of xenon gas, if required, for x-ray protection;

(d) providing chamber designs that meet the no-public-evacuation criterion, minimize radioactive waste volume and intensity, and limit the routine release of radioactive inventories to acceptable levels;
(e) for determining the feasibility of meeting IFE target cost and safety goals (applies to both laser and heavy ion fusion).

Description and key Issues:

Design of thick liquid wall chambers with vented jets and beam port protection requires knowing how smooth and how far free liquid jet surfaces (fixed and oscillating) can be maintained at power-plant relevant geometries and dimensionless Reynolds and Weber numbers. Also required are the vapor condensation rates, droplet clearing rates, and flow recovery rates that would limit the pulse rate of thick-liquid-wall chambers. The outcome of these issues will determine if thick liquid wall chambers are feasible and which driver and target combinations can use them.

The reduction of thermal conductivity and retention of tritium in low activation composite materials, as a function of neutron fluence, composite morphology, and at elevated operating temperatures, is uncertain and needs to be better determined. Understanding the useful lifetime for dry-wall chamber lifetime is key to the application of the direct-drive approach to IFE, affecting target design, chamber design, and target technology.

For accelerators it is necessary to determine what shielding geometries and compositions maximize lifetime of final focus magnets in the presence of neutron and gamma transport through shielding structures with a large number of long, narrow penetrations. For lasers it is necessary to understand the fundamental mechanisms that set the threshold for laser damage of reflective and transmissive laser optics, and how those thresholds change with radiation and debris contamination. Understanding the driver-chamber interface issues will be key to the choice of the optimal number of laser or ion beams needed for each driver; this will be an important input on symmetry to target design and target fabrication, and will affect neutron leakage and safety.

Improved understanding of radionuclide release fractions from various solid and liquid fusion materials, and of the potential for end-of-life processing of those materials, can have an important impact on the required levels of safety assurance, and on the public acceptance of future DT-burning experiments and fusion plants. Better knowledge of safety impacts of chamber design choices will lead to a better understanding of which combinations of targets and chambers are better from an environmental public acceptance point of view.

To minimize tritium inventory, it is necessary to identify capsule materials and target designs, which allow fast tritium fill, and can tolerate transient heating and acceleration during injection, while preserving ablator smoothness and geometrical precision required for high gain implosions. To minimize activated material volumes, it is necessary to identify high-Z hohlraum materials and mixtures that can be mass manufactured at low cost, can be readily recycled from chamber debris outflow, and retain high wall x-ray albedos for good coupling efficiency. Understanding what practical target materials and fabrication methods can be used for IFE will provide useful guidelines on the choice of materials, geometry, and surface roughness that should be assumed in target designs. The research on materials will also affect safety, as target debris can contribute significantly to radioactive inventories in IFE.

Implementation Approaches:

3.6.5.1 The PoP liquid chamber experiments should take advantage of the modularity of liquid-jet pockets by performing experiments with single scaled jets and clusters of a few jets, allowing extrapolation to the much larger flow and power levels that will be required in later Performance Extension experiments. PoP experiments should also take advantage of the large differences in time scales of groups of phenomena, separating studies of slow liquid hydraulic response from studies of rapid ablation and venting phenomena. Tasks are liquid jet hydraulics--free jet formation, vortices and wetted walls; liquid shock response-- shocks and droplet clearing, high-strain-rate liquid response; plasma/vapor condensation—superheated vapor condensation, diagnostics development, and shock interaction with structures; design, modeling and system studies; additional studies—Flibe chemistry, structure corrosion and erosion, tritium and hohlraum materials recovery, and HIF target x-ray/debris calculations. Pulsed x-ray irradiation candidate liquid materials may be studied on existing z-pinch x-ray sources.

3.6.5.2 Dry wall chamber research deals mostly with structural materials that are low activation (e.g., carbon and silicon carbide composites) and intended to operate at low pressures and stresses, and at much higher temperatures (1500 degrees Centigrade) than usually considered for MFE blankets. First wall response to pulsed soft x-rays, and final optics protection from target radiation/debris are key areas. The tasks are first wall/blanket—materials development, radiation damage studies, flowing granular beds, and tritium implantation/retention; fireballs and chamber dynamics—fireball experiments using pulse z-pinch x-ray sources, fireball modeling, and gas-filled chamber dynamics; and systems design, modeling and analysis. Pulsed x-ray irradiation of carbon composite dry-wall materials may be studied on existing z-pinch x-ray sources.

3.6.5.3 For heavy-ion driven IFE final focus magnets: Use 3-D neutron transport codes, working in partnership with the heavy-ion driver physics design for final focus ion optics and the heavy-ion target designs, to seek a self-consistent design for final-focus magnets consistent with heavy ion target requirements and the standoff of protected wall chamber designs. For laser-driven IFE final optics: Perform experiments and simulations on laser and neutron damage of grazing-incidence metal mirror and fused silica. Explore alternative final optic protection (e.g., liquid metal film mirrors), gas protection/shock-tube experiments, and repetitive pulsed power experiments.

3.6.5.4 Both experimental data as well as numerical simulations are to be performed of the mobilization, diffusion, and transport of radionuclides in various candidate materials at elevated temperatures. Studies of ways to minimize waste disposal volumes, such as maximum use of recycling, as well as minimizing hazard levels are important. Tasks to improve understanding include:

- Improved data on important radionuclide release fractions (including hohlraum materials).
- Measurement of tritium inventories in high temperature C-C composites (laser chambers).
- Creation and validation of dust/aerosol transport models.
- Updated safety analyses using estimates for accident temperature excursions and new radionuclide release data.
- Identification of methods to control and remove coolant impurities (target-debris and corrosion products) for liquid wall chambers.
- Tritium recovery and control methods (compatible with the chamber structure material and plant designs).
- Identification of methods for recycling and/or clearance of activated materials.
- Improvements in overall safety and environmental characteristics of current chamber/plant designs.

3.6.5.5 Methods of low cost manufacture and rapid injection need to be identified, and candidate prototype targets tested for compatibility with IFE injection into representative IFE chamber environments. Promising candidate IFE target designs need to be tested both on a target injector test stand that can simulate IFE chamber environments, as well as on existing laser facilities to determine both the achievable and required target tolerances, precision and injection compatibility for IFE. A coordinated design effort is required of both IFE target fabrication and IFE target physics design groups working in partnership. Fabrication tasks to develop the required knowledge include:

- Development and testing of foam materials, barrier layers, and high-z coating processes.
- Evaluation and recommendations for scalable manufacturing techniques for direct and indirect drive targets.
- Experiments on fuel layering inside overfilled foam shells.
- Evaluation of material properties at cryogenic temperatures (DT and other target components).
- Study on permeation filling vs. cryogenic injection filling.
- Fill facility concept and required tritium inventory for each target design.
- Radiation damage data for membranes and foams.
- Demonstration of filling and layering of target concepts.

Target injection tasks to develop the required knowledge include:

- Construction of a more capable injection system.
- Demonstration of ability of cryogenic hohlraums to withstand accelerations.
- Measurements of DT ice strength and predictions of acceleration effects on targets.
- Measurement of thermal radiation effects on DT filled and layered cryogenic targets.
- Modeling of target chamber gas effects on target injection.
- Demonstration of hitting an indirect drive target on the fly.
- Demonstration of injection and tracking of direct drive targets.
- Examine effects of rapid warm up (< 20 msec) on DT ice layer.

3.6.6 IFE CONCEPT EXPLORATION

5-Year Objective: Concept exploration (CE) level research should be performed on advanced drivers and targets that have potential for major improvements in IFE.

Performance will be measured by understanding the key feasibility issues for exploratory IFE concepts, enough to decide if any should advance to the proof-of-principle stage.

Description and Key Issues:
Concepts that may potentially make dramatic reductions in driver energy or cost could reduce the cost of electricity significantly, and also reduce the cost of development of IFE. Approaches that have this potential have issues for which little present data exists, so initial exploratory work would be needed, but limited to the most critical and difficult feasibility issues associated with each concept.

Implementation Approaches:
3.6.6.1 Z-pinch driven IFE: The most important issue is to determine if the recyclable pulsed-power transmission line can have acceptable electrical and structural properties, and can be replaced and recycled for an acceptable cost and repetition rate. Initial studies could include demonstration experiments of a scaled model transmission line composed of suitable power plant coolant materials, investigation of shock mitigation techniques using solid Li packing (with variable density) in the chamber, and a pre-systems power plant optimization and analysis including cost estimates for the recycle and remanufacture of the transmission lines.

3.6.6.2 Fast ignition: The most fundamental issue is how to couple the intense laser light to pre-compressed fuel cores through the ablated plasma left after the implosion of the fuel. Needed are target designs that minimize the amount of ablated plasma that the igniter beam has to travel through, and experiments on intense laser penetration through representative plasmas using existing short-pulse laser facilities.

3.6.6.3 New concepts integrating new targets, drivers and chambers in synergistic combinations that simplify design, lower cost of electricity, and improve reliability.

4.0 Planning and Implementation (Level 3)

This section provides a description and status report of the development of a Level 3 database and database management system for the Integrated Program Plan.

In its review of the Fusion Energy Sciences program in 1999, the DOE Secretary of Energy Advisory Board (SEAB) stated, “Given constrained budgets, the wide variety of options, and the linkages of one issue to another, increasingly sophisticated management of the program will be required…(and) given the complex nature of the fusion effort, an integrated program planning process will be required.”

The Charter from OFES to the IPPA Working Group requests that an Integrated Program Plan be prepared which includes the following information and capabilities:

- description of the program activities
- intermediate milestones for each activity
- interrelationships among the activities
- linkages between program accomplishments and program goals
- basis for performance-based management of the program
- basis for resource planning
- basis for establishing accountability

These SEAB and OFES requirements can be most readily accomplished by the creation and use of a research activities database and a concomitant database management system for the fusion program.

4.1 Program Activities and Categories

As a matter of policy the DOE Office of Fusion Energy Sciences (OFES) uses peer review processes as the primary mechanism for evaluating proposals, assessing progress and quality of work, and for initiating and terminating facilities, projects, research programs, and groups. The OFES organizes peer and expert reviews of proposals from universities, national laboratories, industry and other institutions, and conducts ad hoc reviews of subject areas. The OFES allocates funds to achieve program balance and to accomplish program goals, utilizing advice received from its Fusion Energy Sciences Advisory Committee (FESAC) and taking into account perspectives developed in specialized community committees and meetings. The effectiveness of this management approach depends on good communication mechanisms, ready access to data on how program resources are being allocated, the anticipated deliverables and milestones targeted by program performers, and a formalism for discussing interdependencies of the various program elements and tasks. Currently over 300 specific research activities (tasks) are funded each year. The basic management functions performed by the OFES staff include program planning, implementation and performance monitoring.

To assist in the development of a more sophisticated management system, as recommended by SEAB, the Working Group has begun the process of developing a relational database that can be used by DOE management and field researchers to obtain the data necessary for discussing program priorities and optimizing the allocation of program resources.

As a first step, we have grouped the ongoing research activities into a set of categories, the Research Activities Structure (Table 4.1). One requirement is that there be direct traceability between this structure and the existing OFES budget structure, so that funding information can be easily tracked. The Research Activities Structure has been developed in close cooperation with the OFES staff and with some community input, and may undergo revisions in the future.

Table. 4.1 Research Activities Structure.

1.0	**Theory and Computation**
1.1	Magnetic Confinement
1.2	Inertial Fusion
1.3	Plasma Simulation
1.4	Basic Plasma Theory
2.0	**Experimental Science**
2.1	Experiments on National MFE Facilities
2.2	Other MFE Research
2.3	Inertial Fusion Drivers
2.4	Other IFE Research
2.5	International Collaborations
2.6	Diagnostics and Other
3.0	**Enabling Technologies Research**
3.1	Plasma Technologies
3.2	IFE Technologies
3.3	Fusion Technologies
3.4	Materials Research
3.5	Advanced Design and Analysis
4.0	**General Science and Applications**
4.1	Atomic Physics
4.2	Education, Outreach and Conference Support
4.3	NSF/DOE Partnership on General Plasma Science
4.4	Applications Research and Other General Science
5.0	**Infrastructure**
5.1	SBIR/STTR
5.2	Decommissioning and Waste Management
5.3	General Plant Projects
5.4	Other

The research categories in Table 4.1 can be correlated to the six top level FESAC program goals, which are summarized in Table 4.2. The results of this correlation can be displayed in matrix form, as shown in Table 4.3. In this correlations matrix, P refers to a primary relationship and S refers to a secondary relationship. Other more detailed matrices, relating the research activities (tasks) to the FESAC five-year objectives (see Chapter 3), can also be constructed.

Table 4.2 FESAC Program Goals.

G-1 Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and computation.

G-2 Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems, by investigating a broad range of innovative magnetic confinement configurations.

G-3 Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.

G-4 Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.

G-5 Advance the fundamental understanding and predictability of high energy density plasmas for IFE, leveraging from the ICF target physics work sponsored by the National Nuclear Security Agency's Office of Defense Programs.

G-6 Develop the science and technology of attractive rep-rated IFE power systems, leveraging from the work sponsored by the National Nuclear Security Agency's Office of Defense Programs.

Figure 4.3 Matrix of Activities vs. Goals.
(P refers to a Primary Relationship and S refers to a Secondary Relationship)

	G-1	G-2	G-3	G-4	G-5	G-6
1.1 Magnetic Confinement Theory	P	P	P	S		
1.2 Inertial Fusion Theory					P	S
1.3 Plasma Simulation	P	P	P	S	P	S
1.4 Basic Plasma Theory	P	P	S		P	
2.1 National MFE Facilities	P	P	P	S		
2.2 Other MFE Experiments	P	P		S		
2.3 IFE Drivers					S	P
2.4 Other IFE Research					P	S
2.5 International Collaboration	S	S	P	S	S	S
2.6 Diagnostics	P	P	P	P	P	P
3.1 Plasma Technologies	S	S	P	P	S	P
3.2 IFE Technologies				S		P
3.3 Fusion Technologies			S	P		S
3.4 Materials Research		S	S	P		P
3.5 Design and Analysis	S	P	P	P	S	P
4.0 General Science and Applications	P	S	S	S	P	S

4.2 Research Activities Database

Choice of software. The database (DB) is being constructed using a commercially available, web-compatible, relational DB applications program. The software chosen is Microsoft ACCESS, which has become a PC standard for robust, modern databases. It is widely available in Microsoft OFFICE and has the important property of *referential integrity*, which means that a system of internal consistency checks is automatically performed as one goes along, preventing many chances for error. ACCESS unfortunately will not run on Mac platforms as of this writing but it is expected this may change.

Records (rows). One "Record" for each of the 300+ funded research activities (tasks) will be assembled. Each of these records will consist of a set of "Fields," and each field will contain a specific type of information.

Fields (columns). The complete set of fields has not yet been determined. The fields and their relationships are the subject of current DB design efforts, but at a minimum the DB will probably cover the following fields:

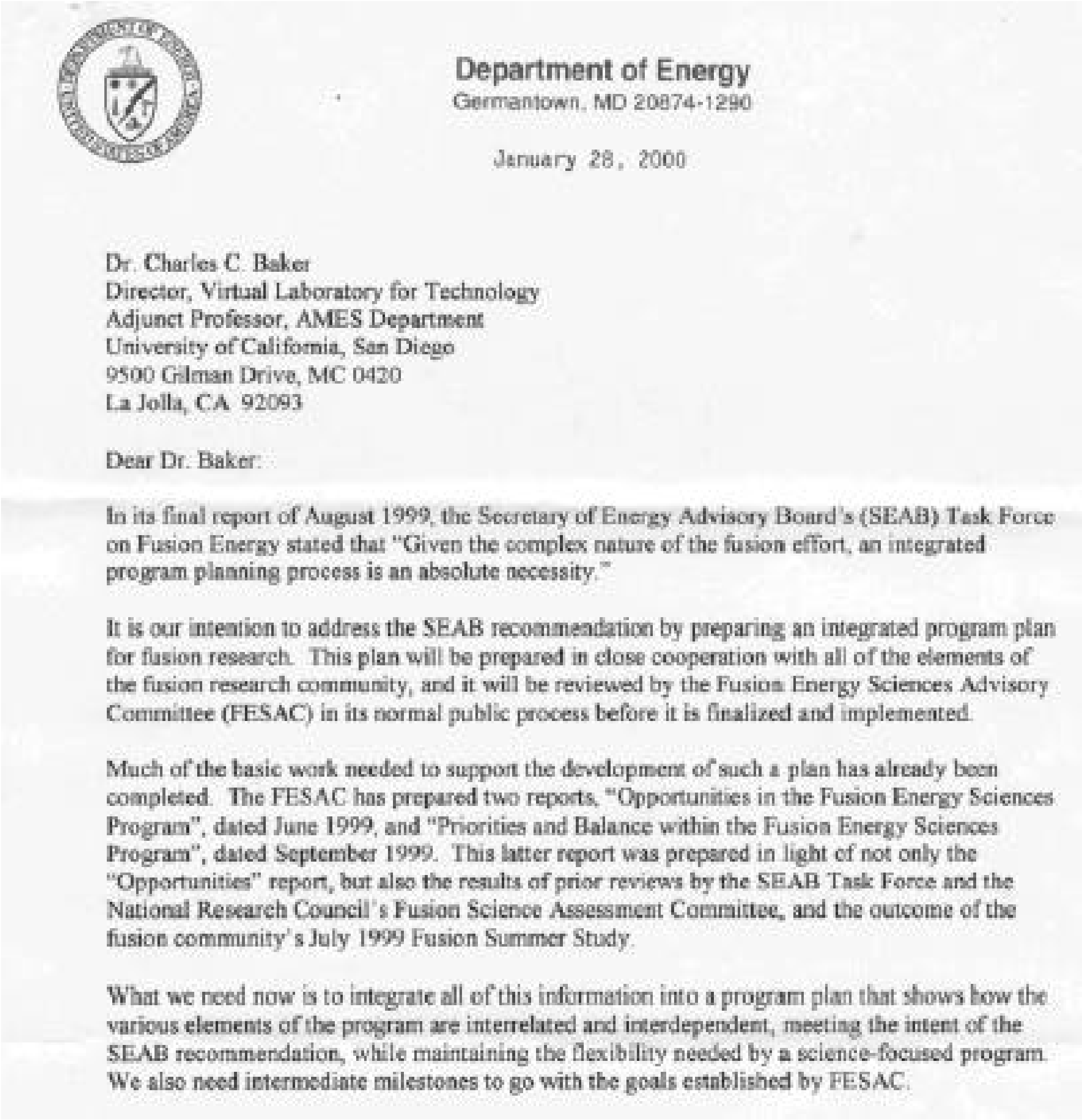
1. Project Title
2. Name of Institution performing work
3. Name of Principal Investigator (PI)
4. PI's email
5. OFES Manager
6. OFES Manager email
7. DOE Budget and Reporting Number
8. DOE Budget and Reporting Category Name
9. IPPA Research Activities Structure Number
10. IPPA Research Activities Structure Name
11. DOE Purchase Request Number (unique Tracking Number , "key" field)
12. Statement of Work
13. Scientific/Technical Approach
14. Statement of Deliverables
15. FY00 Milestones
16. FY01 Milestones
17. FY02 Milestones
18. Outyear Milestones
19. Milestone Performance Discussion
20. Milestone Dates Achieved
21. FY99 Budget - actual
22. FY00 Budget - actual
23. FY01 Budget - request
24. FY02 Budget - request
25. Five-year Budget Projections
26. Relation to FESAC Goals and Objectives (Primary or Secondary)
27. Connection & linkages to Other Tasks
28. Connection & linkages to Scientific Issues

The database can be queried to find information of interest. Criteria can be entered in a query to specify what information one wants to find. For example, a query could be made to list all the performers doing research related to, e.g., FESAC Goal 3.1. Reports can also be generated from the database that summarizes data selected from the database.

The database will be implemented in step-wise fashion by first preparing a smaller set of task records involving representative examples from experiment, theory, technology, and basic science areas, and including both MFE and IFE. This smaller test database has already been created and is being used to study various possible field combinations; uncover bugs; illustrate how the database will work; practice queries, transmittal of data, and web applications; and aid the final DB design.

Once the format (template) for creating the Records, including an agreed upon set of Fields, has been established, the 300+ Principal Investigators will be asked to provide the required data. OFES staff would review and approve this data and have it entered into the database. Once entered it would be available to all members of the fusion community through a web-based interface. However, access will necessarily be restricted for future year budgeting data of the federal government.

Appendix I
IPPA Commissioning Letter and Charter



Department of Energy
Germantown, MD 20874-1290

January 28, 2000

Dr. Charles C. Baker
Director, Virtual Laboratory for Technology
Adjunct Professor, AMES Department
University of California, San Diego
9500 Gilman Drive, MC 0420
La Jolla, CA 92093

Dear Dr. Baker:

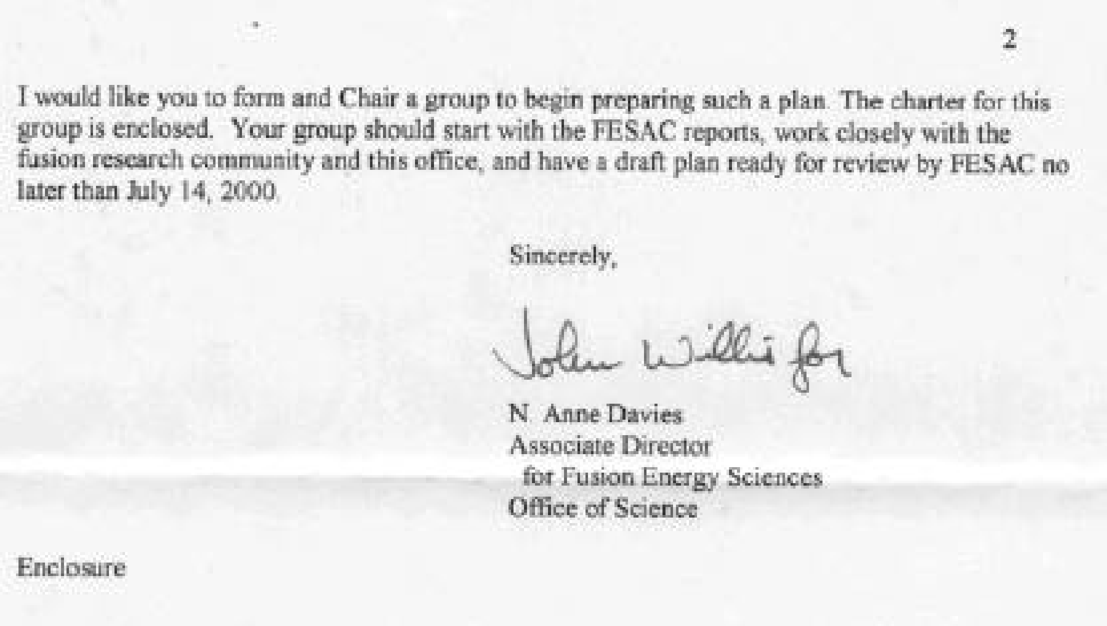
In its final report of August 1999, the Secretary of Energy Advisory Board's (SEAB) Task Force on Fusion Energy stated that "Given the complex nature of the fusion effort, an integrated program planning process is an absolute necessity."

It is our intention to address the SEAB recommendation by preparing an integrated program plan for fusion research. This plan will be prepared in close cooperation with all of the elements of the fusion research community, and it will be reviewed by the Fusion Energy Sciences Advisory Committee (FESAC) in its normal public process before it is finalized and implemented.

Much of the basic work needed to support the development of such a plan has already been completed. The FESAC has prepared two reports, "Opportunities in the Fusion Energy Sciences Program", dated June 1999, and "Priorities and Balance within the Fusion Energy Sciences Program", dated September 1999. This latter report was prepared in light of not only the "Opportunities" report, but also the results of prior reviews by the SEAB Task Force and the National Research Council's Fusion Science Assessment Committee, and the outcome of the fusion community's July 1999 Fusion Summer Study.

What we need now is to integrate all of this information into a program plan that shows how the various elements of the program are interrelated and interdependent, meeting the intent of the SEAB recommendation, while maintaining the flexibility needed by a science-focused program. We also need intermediate milestones to go with the goals established by FESAC.

Appendix I (continued)



2

I would like you to form and Chair a group to begin preparing such a plan. The charter for this group is enclosed. Your group should start with the FESAC reports, work closely with the fusion research community and this office, and have a draft plan ready for review by FESAC no later than July 14, 2000.

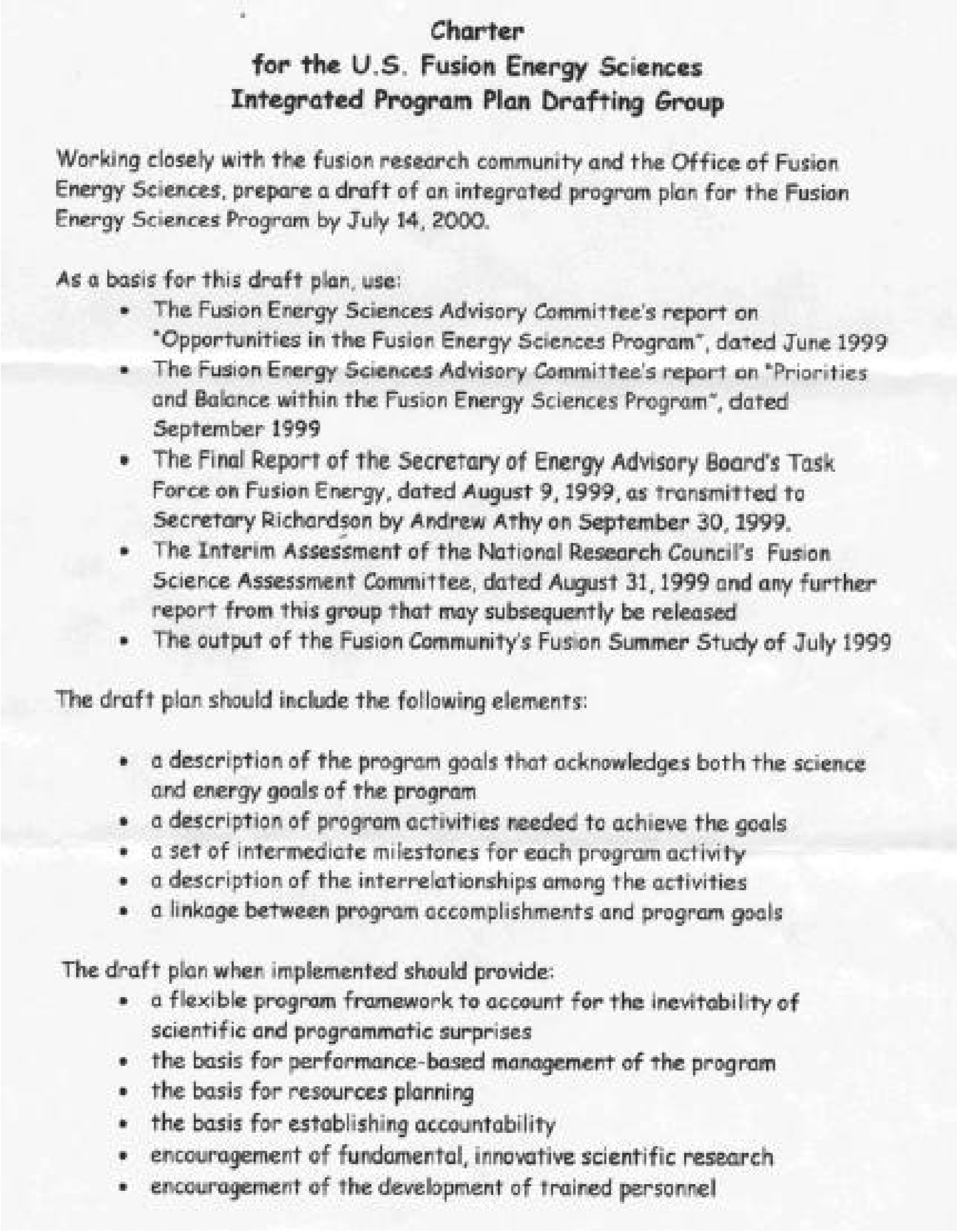
Sincerely,

John Willis for

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

Enclosure

Appendix I (continued)



Charter
for the U.S. Fusion Energy Sciences
Integrated Program Plan Drafting Group

Working closely with the fusion research community and the Office of Fusion Energy Sciences, prepare a draft of an integrated program plan for the Fusion Energy Sciences Program by July 14, 2000.

As a basis for this draft plan, use:

- The Fusion Energy Sciences Advisory Committee's report on "Opportunities in the Fusion Energy Sciences Program", dated June 1999
- The Fusion Energy Sciences Advisory Committee's report on "Priorities and Balance within the Fusion Energy Sciences Program", dated September 1999
- The Final Report of the Secretary of Energy Advisory Board's Task Force on Fusion Energy, dated August 9, 1999, as transmitted to Secretary Richardson by Andrew Athy on September 30, 1999.
- The Interim Assessment of the National Research Council's Fusion Science Assessment Committee, dated August 31, 1999 and any further report from this group that may subsequently be released
- The output of the Fusion Community's Fusion Summer Study of July 1999

The draft plan should include the following elements:

- a description of the program goals that acknowledges both the science and energy goals of the program
- a description of program activities needed to achieve the goals
- a set of intermediate milestones for each program activity
- a description of the interrelationships among the activities
- a linkage between program accomplishments and program goals

The draft plan when implemented should provide:

- a flexible program framework to account for the inevitability of scientific and programmatic surprises
- the basis for performance-based management of the program
- the basis for resources planning
- the basis for establishing accountability
- encouragement of fundamental, innovative scientific research
- encouragement of the development of trained personnel

Appendix II
IPPA Steering Committee & Working Group Membership

IPPA Steering Committee

John Lindl, Chair
(LLNL)

Stewart Prager, Vice-Chair
(Univ. of Wisc.)

Steven Cowley
(UCLA)

Richard Hawryluk
(PPPL))

Thomas Jarboe
(U. of Wash.)

Earl Marmar
(MIT)

Kathryn McCarthy
(INEEL)

Richard Siemon
(LANL)

Ronald Stambaugh
(GA)

IPPA Working Group

Charles Baker, Chair
(UCSD)

Stephen Dean
(FPA)

William Ellis
(Raytheon Eng.)

Richard Hazeltine
(U. of Texas)

Grant Logan
(LLNL)

Michael Mauel
(Columbia U.)

Ned Sauthoff
(PPPL)

Tony Taylor
(GA)

Appendix III
Scientific Issues of Fusion Science

Scientific Issues of Fusion Science

A central goal of the fusion energy science program is to advance the fundamental understanding of the plasma state.[1] Advances in understanding will occur as each of a sequence of scientific and technological questions is identified, investigated, debated within the community and finally answered. In this Appendix we display a representative assortment of such questions, emphasizing those that carry particular leverage for the progress of fusion research.

The following list does not pretend to be definitive. Rather it is intended to convey the flavor and thrust of current research activities by displaying examples of the questions that fusion scientists are asking. The list is organized using a set of major research challenges identified by the Fusion Energy Sciences Advisory Committee (FESAC)[2]; most of the italicized sentences beginning each section are drawn from FESAC documents.

III.1. Transport and Turbulence

What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled? Key underlying issues are:

What are the mechanisms responsible for anomalous electron thermal transport? The fusion program has made substantial progress in explaining ion thermal transport, using models in which instabilities caused by the ion temperature gradient drive the turbulence. However, recent experimental observations, including experimental studies of thermal barriers, reveal the decoupling of ion and electron thermal transport: one transport channel is observed to vary significantly with plasma conditions while the other is unchanged. In recent years, improvements in diagnostic systems have allowed measurement of the thermal diffusivity with unprecedented accuracy, lending quantitative support to the hypothesis that separable mechanisms are at work for the two species. Electron transport will be especially important in reactor systems, where the collisional equilibration time is necessarily much smaller than the confinement time.

This problem can only be addressed by a coordinated effort in theory, modeling and experiment. An essential element of the investigation will be the development and deployment of diagnostics capable of observing the short-wavelength modes that may play an essential role in electron transport. Theory and simulation must also be extended to the shorter length scales, and enlarged to describe electromagnetic effects more completely. The understanding gained will apply to non-fusion plasmas, particularly those of astrophysical and space sciences interest.

How does the power threshold for internal transport barriers scale with gyroradius in the absence of externally driven rotation? It is generally agreed that *E x B* shear-stabilization of microturbulence explains the formation of internal transport barriers. Commonly, the *E x B* rotation is induced primarily by external beam-driven toroidal rotation. However, even without external drive, plasma diamagnetism tends to induce the *E x B* rotation. There is some evidence that, in the absence of external drive, the power threshold increases significantly with increases in the magnetic field. This correlates with a reduction in ρ_* (the ratio of gyroradius to system size) and diamagnetic rotation. This is a worry for large tokamak reactors, which have lower ρ_* and usually weak toroidal rotation.

We need to be able to predict the threshold power scaling, which is related to the possibly more important and certainly more difficult question of how H-mode power thresholds scale. The physics and field

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[1] *Priorities and Balance within the Fusion Energy Sciences Program*, Report submitted to the US Department of Energy by the Fusion Energy Sciences Advisory Committee, September 1999.

[2] *Opportunities in the Fusion Energy Sciences Program*, Fusion Energy Sciences Advisory Committee, June 1999.

scaling of the two effects are in fact quite similar, apart from the added complications associated with divertor physics in the edge region. The recent progress in understanding internal transport barrier formation, and its incorporation into transport models, suggest that we will soon be able to answer the power-scaling question quantitatively. Such answers will provide the key to prediciting H-mode thresholds.

How important are nonlocal and finite ρ_* effects on transport? Traditional models of anomalous transport have usually assumed the underlying microturbulence to be local, depending on only the local plasma parameters and gradients. This picture leads to a gyro-Bohm scaling for diffusivity ρ_*^2 reflecting a random walk with step-size (or mixing length) proportional to the gyroradius. Experiments in the early 90's showed this was not always the case: diffusivity sometimes displayed a much worse Bohm scaling, proportional to the gyroradius rather than its square. The most recent measurements indicate that the mixing length still scales with ρ_*, but the correlation rate decreases with increasing ρ_* in the direction to produce Bohm scaling. This observation fits quite well with the idea that diamagnetically induced *E x B* rotational shear is stabilizing. *E x B* shear has a nonlocal character, since the potential is determined globally, but it is easier to treat than other finite-ρ_* effects, such as shear in the driving temperature gradients.

Improved codes able to treat these nonlocal effects are under development---and very computationally challenging. However, with the advent of terascale parallel computing platforms, we will be able to attack these questions in a few years.

What is the theoretical and experimental basis for local control of tokamak transport, including the ability to predict the position, strength and dynamics of transport barriers? Advanced tokamak fusion reactors would take advantage of the ability to control plasma profiles. Such a machine would need to run with a pressure profile that remains stable with respect to magnetohydrodynamics (MHD) while driving a large bootstrap current. This cannot be accomplished by the heating profile alone---control of both particle and thermal transport will be required. Particle confinement must not be too large lest accumulation of helium ash and other impurities would spoil the discharge.

Edge barriers, which typically serve as the boundary condition for core confinement, represent a special challenge. The effects of neutrals, x-point topologies and the coupling to plasma on open field lines must be included. The widely used transport-control method based on flow shear is also applicable to ordinary non-ionized fluids, making advances in fusion transport control relevant to astrophysics, fluid dynamics and atmospheric and oceanic sciences.

What are the effects of finite-beta and confinement geometry on transport? Much of the progress in analysis and simulation of microturbulence has come from electrostatic codes, with adiabatic passing electrons, in idealized (circular) tokamak geometries. This is adequate for obtaining qualitative agreement with most tokamak data. However it will be quite inadequate for betas approaching the MHD beta limit or for the highly distorted geometries of new low aspect ratio devices. While linear MHD and gyrokinetic stability codes have been able to deal with this regime in the past decade, only in the past year have nonlinear simulation codes become operative. More years of developing and running these codes will be required for predictive capability.

III.2. Plasma Fluid Behavior and Macrostability

What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems? Key underlying issues are:

Appendix III (continued)

What is the fundamental origin of the observed density limit on tokamak operation? The density limit defines one of the fundamental operational boundaries for magnetic confinement devices. For the tokamak, extrapolated reactor performance depends critically on the limit. There is a growing consensus on the mechanism for a density-limiting disruption: As the density rises, the edge plasma cools, increasing the local resistivity and reducing the plasma current density. As the current channel shrinks, the overall MHD equilibrium becomes unstable and a disruption ensues. However, while explaining the mechanism of the final collapse, this picture cannot explain the value or scaling of the density where the collapse occurs. Limits based solely on edge power balance and stability predict relatively strong dependence on input power and plasma purity, dependences that are not observed experimentally. Further, while in many devices a radiative collapse only occurs near the density limit, in other cases the relation between radiative collapse and the density limit is not clear. Advances in edge modeling coupled to improvements in measurements of edge profiles and fluctuations should allow substantial progress in this area.

What are the beta limits set by the formation of magnetic islands and loss of flux surfaces? In axisymmetric configurations, magnetic islands arise through pressure-driven tearing instabilities. In stellarators, pressure-driven equilibrium currents produce magnetic islands, giving an equilibrium beta limit. The physics of pressure driven islands in these two contexts is closely related. The effect of the Pfirsch-Schlüter currents on islands in 3D equilibria is predicted to be determined in part by the resistive interchange criterion. Perturbed bootstrap currents are predicted to play a major role in both contexts, giving the neoclassical tearing mode in tokamaks and the possibility of island healing in stellarators. A major puzzle in the tokamak context is the determination of what stabilizes the neoclassical tearing mode at small island widths, and thus sets a threshold for the metastable state. (The ion polarization drift has been regarded as the likely candidate, but recent theoretical work casts doubt on this.) Since the beta threshold for the onset of metastability seems to be set by finite gyroradius effects, it is likely to be low in a tokamak reactor, making this a critical reactor issue. The calculation of island formation in three-dimensional magnetic fields is related to the general issue of island formation in Hamiltonian systems, particularly to the self-consistent problem where the Hamiltonian is affected by the integrability properties of the orbits. This matters, for example, in toroidal accelerators where particles are required to be confined for many orbits.

How does one calculate long timescale evolution in a plasma without significant separation of spatial and/or temporal scales? What replaces our usual notion of solving diffusion equations? This question arises from considering either:

(a) the possibility of avalanches in the plasma core, where the bulk of the heat may be carried by rare events with long spatial scales; or

(b) confinement in short-scale-length regions (e.g. the edge, transport barriers) where eddy sizes can be comparable with scale lengths.

The answer is likely to be different in the two cases.

A parallel issue arises in the study of certain types of linear instability. Instabilities driven by long mean-free-path mechanisms need a theoretical context as reliable and well understood as MHD. How, for example, should semi-collisional electron kinetics be introduced into fluid/kinetic hybrid descriptions (analytic and numerical) of toroidal plasmas?

How do instabilities in high-pressure plasmas evolve as non-linear effects become important? The criteria for linear stability are well understood for most ideal instabilities. However their nonlinear evolution is less well understood. The nonlinear properties determine whether an instability saturates or grows to large amplitude, and what the consequences of that growth are for the plasma. This is particularly important in understanding and controlling the consequences of instabilities that lead to beta collapses or disruptions. The physics of magnetic field generation by a dynamo represents an important example of nonlinear evolution with applications in fusion plasma physics, astrophysics, and geophysics.

Appendix III (continued)

Non-linear effects can be modeled with existing 3-D nonlinear fluid-based codes such as M3D and NIMROD, but the physics model underlying these codes does not fully describe the finite gyroradius, long mean-free-path processes that matter. A successful attack on this issue is likely to require increased resolution and speed of the codes, as well as a significant advance in plasma diagnostics. The complexity of nonlinear instabilities calls for high time-resolution, two- and three-dimensional measurements of the plasma's temperature and magnetic structure.

Is it possible to track the approach to instability thresholds in real time, and can the instabilities be avoided or stabilized through active control? Active control of internal profiles or of the instabilities themselves is likely to be needed for reliable fusion plasma operation near stability limits. The most commonly cited needs are stabilization of the resistive wall mode and neo-classical tearing modes, but this is an area with applicability to a wide range of magnetic confinement concepts and instabilities. The resistive wall mode in particular is an important issue for many magnetic confinement devices. The diagnostic techniques for detection of instabilities, and the means of control (RF heating and current drive, for example) encompass a wide range of plasma science. The profile control methods that could be used to avoid instabilities are the same as those that could be used for non-inductive current drive and control of transport properties.

Active control and avoidance of MHD instabilities is in its infancy. Improved diagnostic measurements along with localized heating and current drive sources, now becoming available in many devices, should allow active feedback control of the internal profiles in the near future. Real-time analysis of profile data, such as Motional Stark Effect (MSE) current profile measurements, and real-time identification of stability boundaries are essential components of profile control that require development. A proof-of-principle experiment in the Joint European Tokamak (JET) suggests that active measurement of the damping rate of stable MHD modes is a possible means of identifying stability boundaries. Experiments on localized radio-frequency (RF) current drive to reduce or eliminate neoclassical tearing mode islands have begun in several tokamaks. Stabilization experiments using external magnetic perturbations with open-loop and closed-loop control have also begun in tokamaks. There is a need for additional modeling of resistive wall mode feedback control, and an understanding of its interaction with plasma rotation.

How do the heating and transport properties of high-pressure plasmas influence their MHD stability? Ideal MHD indicates that stable, high-pressure profiles can be identified in several regimes. However experiments have shown that these are achieved only transiently, as heating and transport of thermal energy and current density modify the profiles. Edge-localized modes (ELM's), neo-classical tearing modes, sawteeth are examples of instabilities that are triggered by heating and transport properties. A fusion plasma will likely be more self-organized than present experiments: in true steady-state operation, in order to avoid large amounts of recirculating power, the current density profile must not differ greatly from the bootstrap current profile and the pressure profile must not differ greatly from the profile determined by transport and alpha heating. Configurations must be developed through modeling and experiments in which these self-consistent pressure and current density profiles also have good stability properties.

Integrated modeling of transport and stability is needed in order to develop self-consistent profiles that are compatible with high pressure, good energy confinement, and steady state operation. Open-loop optimization of the pressure and current density profiles with external heating and current drive sources is routinely used in many devices, but long-pulse experiments are needed to demonstrate the consistency of these profiles with steady-state operation.

Can electromagnetic self-organization produce magnetic configurations with good confinement? Electromagnetic self-organization is a common aspect of many plasmas occurring in nature and in the laboratory. The phenomenon is of basic scientific interest, and it might lead to cost-effective magnetic confinement systems for fusion plasmas by minimizing magnetic hardware requirements. However, electromagnetic self-organization necessarily involves symmetry-breaking and reconnection of the magnetic field. In laboratory experiments, such as reversed-field pinches (RFP's) and spheromaks, such symmetry breaking often results in chaotic magnetic fields with poor confinement.

Better understanding of self-organized configurations will require a vigorous experimental program as well as theoretical and computational advances. In particular, studies of fluid behavior must be extended into regimes with higher magnetic Reynold's number. Effects outside the conventional domain of two-fluid MHD may also need to be included.

Learning whether self-organization can yield good confinement will have a clear impact on the magnetic fusion program. If the result is positive, it will improve the economics of fusion reactor concepts, leading to earlier deployment of energy-producing facilities. If negative, tokamak alternatives will need to rely on tailored current profiles (sustained with radio-frequency current drive, for example, or created transiently) rather than naturally occurring activity.

The question also bears on solar and astrophysical processes, where the role of electromagnetic activity and magnetic confinement can be important factors. If coronal loops yield plasma confinement or anomalous heating during periods of activity, these phenomena would affect the thermodynamics of the corona, where high temperatures are not explained. On a larger astrophysical scale, magnetic fields appear throughout the universe. Objects such as collimated jets suggest a form of plasma confinement and heating with a basis in nonlinear magnetic field evolution and self-organization.

How can kinetic and finite gyroradius effects be incorporated into fluid plasma models? Simple magnetohydrodynamic fluid models of plasmas have had impressive success in predicting the macroscopic behavior of toroidally confined plasmas. However, at high temperature, physical effects outside the MHD description can alter MHD predictions significantly. Such non-MHD processes include resistivity, neoclassical and other kinetic effects, plasma flow and flow shear, two-fluid (or drift-MHD) effects, finite Larmor radius, and the role of open field lines. A critical issue for plasma theory and modeling is to extend the MHD model by including the relevant kinetic and two-fluid effects in a fluid formulation. The basic scientific challenge is to derive fluid closures of the appropriate kinetic equation that contain the necessary physical effects, and yet are simple enough for practical computation. A further challenge is then to obtain an accurate and economical numerical solution of the resulting equations.

A particularly important example of a non-MHD effect significantly modifying the MHD stability prediction is the behavior of neoclassical tearing modes (NTM). The basic mechanism relies upon the presence of a bootstrap current in the plasma. Since the amplitude of the bootstrap current becomes large in the low collision frequency regime, NTM stability is a critical issue in high temperature plasmas. In some plasma configurations, a helical deformation of the bootstrap current profile produces a destabilizing effect on the nonlinear dynamics of magnetic islands.

Magnetic reconnection in high-temperature plasmas is modified by long mean-free-path physics. In this regime, time and length scales absent from resistive MHD, such as ion and electron skin-depths and the ion Larmor-radius, enter the problem. In toroidal plasmas, length scales introduced through collisionless orbits, such as the banana width, can modify the instability process. The presence of energetic ions can also modify the stability and reconnection processes in toroidal confinement devices.

Plasmas with low collisionality play important roles throughout the universe. Progress in obtaining accurate and practical mathematical models of the dynamics of these plasmas will have a major impact on models of solar and stellar winds, and coronal disruptions, such as solar flares and mass ejections.

III.3. Wave-particle Interaction

What are the fundamental causes and nonlinear consequences of wave interactions with thermal and non-thermal particles? Key underlying issues are:

Appendix III (continued)

Can RF waves maintain and control desirable confinement in long-pulse or reactor-scale plasmas? In any plasma configuration there are a number of processes, such as instability or spontaneous generation of plasma currents or flows, which drive the plasma to some state---either desirable or not. These processes interact nonlinearly through the plasma profiles: density, temperature, current, toroidal or poloidal flow, or through other properties of the plasma distribution function. Because RF waves are capable of modifying these profiles, they can be used to modify the plasma dynamics. The numerous observations of such modification include heating or current drive on a mode-rational surface, producing or triggering internal transport barriers, and controlling transport in non-axisymmetric devices through the plasma potential. Our challenge is to understand the wave/particle mechanisms quantitatively, through close comparison between theory and experiment, and to develop techniques to employ these mechanisms to our advantage in synergy with the intrinsic dynamical processes.

As an example, plasma rotation plays an important role in MHD stability, and in the formation of edge and internal transport barriers through shear suppression of microturbulence. Most observations of toroidal and polodial rotation have been made in plasmas with external momentum sources, such as neutral beams, making it difficult to separate rotation by direct momentum input and more complex internal mechanisms. Recent experiments on Alcator C-Mod and other tokamaks using ion-cyclotron heating alone have reported similarly large plasma rotations and associated large radial electric fields, despite the much smaller momentum input from the waves. Is this a consequence of transport or wave-particle interaction? Some attempts have been made to modify the neoclassical theory for large rotation to predict the radial electric field. These theories are not completely self-consistent. Mechanisms and theories have also been proposed to account for radial electric field generation by RF waves with some testable predictions. Experiments are needed to validate or disprove these theories. The idea that beneficial plasma rotation can be produced in reactor plasmas by heating systems more efficient that neutral beam injectors remain a very attractive concept.

What are the linear stability thresholds for Alfvén waves in the presence of energetic particles, such as alpha particles in a burning plasma? A complete linear code that could address this question is not yet in operation, although efforts to construct one are underway. Present codes attempting realism cannot treat waves in the MHD continuum correctly (or its natural generalization when the continuum converts into kinetic drift Alfvén waves). At beta values where MHD limits are approached, the MHD thresholds are modified by kinetic particle effects. This aspect of the problem, as well as the onset of energetic particle Alfvén waves in realistic geometry, needs investigation.

Does reversed magnetic shear affect energetic-particle induced instability? Reversed magnetic shear improves the bulk transport of the core plasma. However, shear reversal necessarily leads to regions with low magnetic shear, and it appears to be particularly easy to excite energetic-particle modes in such regions. Hence the compatibility of reversed-shear operation in a burning plasma needs investigation.

What is the nonlinear evolution of kinetic Alfvén excitations induced by hot particles? Past work has been successful in predicting threshold levels and correlating them with experiments in TFTR and JET, as well as with computer simulations. However this work is restricted to cases in which there is a limited number of Alfvén wave excitations and no mode overlap. In these cases there has also been impressive theoretical agreement on JET concerning the effect of nonlinear bifurcations that produce frequency splittings, as well as a roadmap to the chaotic response, even when modes do not overlap. Further progress is needed to obtain a quantitative understanding of energetic particle transport when mode overlap occurs and when large frequency shifts occur. There is at present one theoretical model of how to obtain large and fast frequency shifting effects with a single mode, but this theory does not properly explain many different experimental observations of fast frequency shifting effects that have been observed. An enlarged theoretical model needs development.

Appendix III (continued)

Is there a significant interplay between Alfvén wave excitation by energetic particles and the conventional response of plasmas? There are preliminary indications that the nature of sawtooth oscillations may be altered in the presence of copious Alfvén wave excitation. The rearrangement of energetic particle distribution due to self-excited Alfvén waves may effect internal potentials that effect the formation of internal transport barriers.

III.4. Plasma-wall Interaction

What are the fundamental processes occurring near the boundary of a confined plasma and how can the interaction between the plasma and material surfaces be controlled? Key underlying issues are:

How does neutral hydrogen recycling affect stability and transport? There are speculations that the processes involving neutrals and neutral hydrogen recycling at the wall may significantly affect the physics of plasma anomalous transport. In some cases these speculations are illustrated by theoretical calculations or interpretations of experimental results. A competing view is that neutral recycling results from anomalous plasma transport and wall conditions. In this view, while plasma recycling does not directly affect the physics of anomalous transport, it may significantly alter plasma parameters (by modifying edge conditions, for example). These questions may have far reaching consequences; they can be answered by experiments using non-recycling wall materials such as lithium.

What is the influence of the plasma edge on the plasma core and on the global properties of confined plasma? Fast parallel plasma transport along open magnetic field lines leading to the divertor plate often results in steep perpendicular gradients with striking effects: they may cause instability, and also may be associated with the edge transport barriers. However our understanding of edge stability and the associated turbulent and convective transport remains primitive. It is clear from core turbulence studies that the edge temperature just inside the separatrix, in the absence of transport barriers, determines the maximum core temperature. Therefore we need to understand the physics of tokamaks with a high edge temperature and good global confinement, and whether such confinement is consistent with a tolerable heat load on walls and divertor plates.

What determines the amplitude and width of edge pedestals in plasma pressure and temperature? Typically plasma profiles of density and temperature in a tokamak with divertor do not approach zero at the edge (separatrix) of the confinement region: there is a substantial amount of hot plasma residing in the immediate neighborhood of the separatrix. This pedestal plasma supplies crucial boundary conditions on diffusion in the tokamak interior, and therefore affects conditions throughout the plasma volume. Therefore an understanding of how the pedestal values are determined, requiring more precise knowledge of processes in the edge region, would bring major benefits in understanding and predicting tokamak performance.

What is the most attractive chamber concept for inertial fusion energy? The chamber must be neutronically thick. Liquid flows might yield a long lifetime, benign environmental characteristics, and high availability, but their operation in an environment compatible with ion beam propagation remains to be investigated.

III.5. Beam and Target Physics

What are the limits to charged particle beam transport and focal intensities in the beam current regimes of interest to IFE? Key underlying issues are:

What is the detailed physics of the key processes in beam physics? The processes that must be understood include emittance growth, halo formation, stray electrons, and longitudinal instability. We must determine how they can be described and simulated, and then find their implications for accelerator architecture. To minimize cost, a quantitative understanding is necessary. Such understanding should allow identification of the best way to accelerate a set of intense ion beams---non-neutral plasmas---to several GeV with the required brightness and pulse shape. Key beam requirements are brightness, uniformity, longevity, current, and compactness.

How are intense energy fluxes transported and absorbed in plasmas? With regard to beam transport, we need to identify the best of several possible transport modes, including ballistic modes and alternatives that minimize chamber penetrations. Processes that affect beam transport include beam stripping, neutralization, background gas ionization, and collective interaction processes. The beam absorption issue determines target design. A target for inertial fusion energy must offer good energy gain, suitability for mass production, compatibility with environmental and materials-recycling needs, and robustness to beam aiming errors.

For intense laser beams in long scale-length plasmas, many nonlinear processes often compete to determine the temporal and spatial distribution of the energy deposition.

How do limits on driver intensity and target requirements for irradiation symmetry, hydrodynamic instability, pulse shaping, and fusion ignition impact the gain achievable in inertial fusion targets?

Successful inertial fusion targets involve a complex interplay of physics issues including hydrodynamic instability, irradiation symmetry and pulse shaping. For a given class of targets, requirements for these issues are largely driver independent, but solutions are strongly affected by the physics of absorption of the driver energy and limits to the achievable or usable intensity. Different classes of targets may be more suitable for different types of drivers. For example, targets that require ultrashort pulses are easier for lasers than for ion beams while the geometry of targets suitable for protected wall chambers is currently more suitable for ion drivers than for lasers. Understanding the physics of the various tradeoffs for combinations of drivers, targets, and chambers will have a major impact on the optimal approaches to IFE.

III.6. Fusion Technology

What are the most effective means to address the technological needs of present fusion research activities as well as future fusion reactors? An underlying issue is:

What are the underlying condensed matter physics and engineering mechanics principles that control the life-cycle mechanical performance of materials? The development of fusion energy is a daunting task, which requires the coordinated efforts of plasma physics and engineering sciences. The mission statement for the Advanced Materials Program (AMP) is to ``Develop the materials science base for the development of materials which will enable fusion to be developed as a safe, environmentally acceptable, and economically attractive energy source." One of the key issues associated with any large-scale engineering structure is component lifetime. In non-optimized materials, low-temperature exposure to neutron irradiation can produce unacceptable embrittlement after a dose of <1 displacement per atom (~1 month of full-power operation for a 1 MW/m^2 wall loading). Working in conjunction with materials scientists funded by non-fusion programs, AMP researchers are investigating the physical mechanisms responsible for the determining the lifetime of materials over a wide range of experimental conditions. The mechanical property results obtained on irradiated materials are of direct significance for establishing the feasibility of fusion energy, but in a broader sense provide important insight into the mechanisms of flow and fracture in any material. The recent enhanced emphasis on cross-cutting theory and modeling issues within the Advanced Materials Program will reduce the time and cost to develop a viable fusion energy system. Advanced multi-scale models are being implemented to address losses of work-hardening capacity and fracture toughness in metallic structural materials.