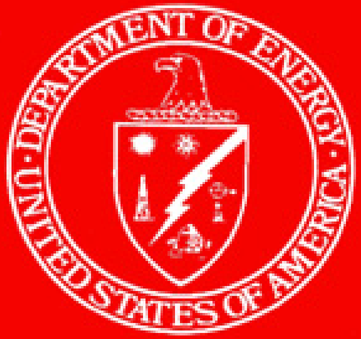
DOE/SC-0041

Fusion Energy Sciences Advisory Committee (FESAC)

Review of
Burning Plasma Physics

September 2001



U.S. Department of Energy
Office of Science

INSTITUTE FOR FUSION STUDIES
THE UNIVERSITY OF TEXAS AT AUSTIN

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October 3, 2001

Dr. James Decker, Acting Director
Office of Science
U. S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Dr. Decker:

On October 5, 2000, Dr. Mildred Dresselhaus charged FESAC to address key questions pertaining to the prospects and value of a burning plasma physics experiment. The Panel formed to address these questions has issued its final report, which was reviewed by FESAC at its meeting on August 1, 2001. This report is enclosed.

FESAC fully endorses the recommendations of the Burning Plasma Panel. In particular, we agree with the Panel recommendation that a burning plasma experiment would bring enormous scientific and technical rewards. We also agree that present scientific understanding and technical expertise allow confidence that such an experiment, however challenging, would succeed.

Yours truly,

RD Hazelt

Richard D. Hazeltine, Chair
Fusion Energy Sciences Advisory Committee

RDH/cv

Enclosure

cc: N. A. Davies
FESAC Members

Department of Energy
Washington, DC 20585

October 5, 2000

Professor Richard D. Hazeltine, Chair
Fusion Energy Sciences Advisory Committee
Institute for Fusion Studies, RLM 11.218
University of Texas at Austin
Austin, TX 78712

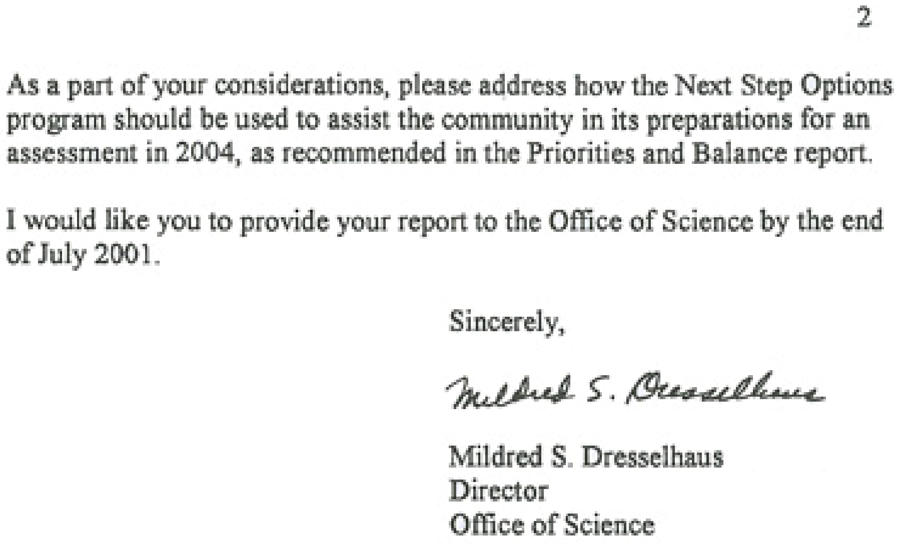
Dear Professor Hazeltine:

For many years, the U.S. magnetic fusion community has recognized that burning plasma physics is the next frontier of fusion research. In this regard, it is important to note that the September 1990 Fusion Policy Advisory Committee report recommended "...construction as soon as possible of the U.S. Burning Plasma Facility." In the last two decades, the program has made several attempts, both international and domestic, to move forward on design and construction of a tokamak experimental device in which the science of burning plasmas could be explored. For various reasons, all these attempts failed.

In the last few years, the U.S. fusion community has reconsidered its priorities and reorganized its efforts. The FESAC Report on Priorities and Balance within the Fusion Energy Sciences Program includes burning plasma physics as a part of a major thrust area, and the draft Integrated Program Planning Activity report includes a section on burning plasma physics. However, the community needs to come to consensus on two aspects of this issue. Therefore, I would like FESAC to address the scientific issues of burning plasma physics, as follows:

1. What scientific issues should be addressed by a burning plasma physics experiment and its major supporting elements? What are the different levels of self-heating that are needed to contribute to our understanding of these issues?

2. Which scientific issues are generic to toroidal magnetic confinement and which ones are concept-specific? What are the relative advantages of using various magnetic confinement concepts in studying burning plasma physics?



As a part of your considerations, please address how the Next Step Options program should be used to assist the community in its preparations for an assessment in 2004, as recommended in the Priorities and Balance report.

I would like you to provide your report to the Office of Science by the end of July 2001.

Sincerely,

Mildred S. Dresselhaus

Mildred S. Dresselhaus
Director
Office of Science

FESAC

Burning Plasma Panel Report

September 24, 2001

Members

Herb Berk	**U. Texas**
Riccardo Betti	**U. Rochester**
Jill Dahlburg	**NRL/GA**
Jeff Freidberg (Chair)	**MIT**
Bick Hooper	**LLNL**
Dale Meade	**PPPL**
Jerry Navritil	**Columbia U.**
Bill Nevins	**LLNL**
Masa Ono	**PPPL**
Rip Perkins	**PPPL**
Stewart Prager	**U. Wisconsin**
Kurt Schoenburg	**LANL**
Tony Taylor	**GA**
Nermin Uckan	**ORNL**

Executive Summary

The Fusion Energy Sciences Advisory Committee (FESAC) panel to investigate burning plasma science was formed in response to a letter to FESAC on October 5, 2000 from Dr. Mildred Dresselhaus, then Director of the Office of Science within the U.S. Department of Energy. Dr. Dresselhaus noted that burning plasma physics has been recognized as "the next frontier of fusion research." She also noted that there have been many attempts over the years by the fusion community to initiate a burning plasma experiment and that burning plasma physics is a major thrust area in recent fusion energy sciences planning documents. Based on these observations Dr. Dresselhaus presented the panel with three charges.

1. What scientific issues should be addressed by a burning plasma physics experiment and its major supporting elements? What are the different levels of self-heating that are needed to contribute to our understanding of these issues?

2. Which scientific issues are generic to toroidal magnetic confinement and which ones are concept-specific? What are the relative advantages of using various magnetic confinement concepts in studying burning plasma physics?

3. How should the Next Step Options (NSO) program be used to assist the community in its preparations for an assessment in 2004, as recommended by the Priorities and Balance report?

The first two charges are scientific and are relatively straightforward to address. The panel agrees that the next scientific frontier in the quest for magnetic fusion energy is the development of a basic understanding of plasma behavior in the regime of strong self-heating, the burning plasma regime. This is the regime in which the internal nuclear fusion reaction by-products dominate the heating of the plasma. Specifically, in the fusion reaction of deuterium and tritium nuclei, very energetic charged alpha particles are produced. The alpha particles are confined in the plasma by the magnetic field. Through collisions with both fuel ions and electrons, the alpha particles transfer their energy to the background plasma. When this self-heating of the plasma by fusion alpha particles is large, the plasma is said to be burning. With a sufficient self-heating, external heating may be turned off and the plasma will be self-sustaining; that is, the plasma is ignited. Producing and understanding the dynamics of a burning plasma will be an immense physics challenge and the crucial next step in establishing the credibility of fusion as a source of energy. This finding has been enunciated by numerous review panels, including the President's Committee of Advisors in Science and Technology Fusion Panel (1995), the Secretary of Energy Advisory Board's Fusion Panel (1999), and the National Research Council Panel in Fusion Energy Sciences (2001).

A number of new phenomena will arise and need to be studied in a burning plasma experiment, depending upon the degree of self-heating. The phenomena include the effects of alpha particles on macroscopic plasma stability, turbulence induced anomalous transport, the strong nonlinear coupling that occurs between multiple simultaneous physical effects, and the dynamics of the fusion burn. The only magnetic configuration sufficiently developed at this time to serve as a burning plasma experiment is the tokamak. Fortunately much of the scientific understanding gained from a tokamak burning plasma experiment will be highly relevant to other toroidal configurations. This is particularly true for areas where reliable theoretical and computational models have been developed and tested against experimental data resulting in a firm foundation from which to address similar issues in related toroidal magnetic configurations, for example, the spherical torus and stellarator. In addition, these issues will be addressed to a somewhat lesser extent in other toroidal configurations such as the reversed field pinch, spheromak, and field reversed configuration.

Although existing and past experiments with weakly self-heated plasmas have been able to investigate some individual scientific issues relating to burning plasmas, they have not and cannot achieve the simultaneous, high performance conditions necessary for a burning plasma. A new experimental facility is needed.

There are presently three burning plasma experimental designs under consideration or development worldwide: ITER-FEAT being developed by the European Union, Japan, and Russia; FIRE being developed in the U.S.; and IGNITOR being developed in Italy. These vary widely in overall mission, schedule, and costs, with ITER-FEAT being the largest endeavor and IGNITOR the smallest in terms of both size and cost. ITER-FEAT is a large superconducting magnetic device while FIRE and IGNITOR are more compact, higher field copper magnetic devices. ITER-FEAT and IGNITOR have received the most extensive designs to date, FIRE the least. Whereas each device would deliver different amounts of scientific information, any of the three facilities would deliver a large and significant advance in our understanding of burning plasmas.

The main conclusions of the panel's deliberations, and upon which our recommendations are based, are described as a series of Findings in the report and are repeated here as follows.

A. Credibility of Fusion as an Energy Option: A burning plasma experiment is the crucial next step in establishing the credibility of magnetic fusion as a source of commercial electricity.

B. The Next Scientific Frontier: The next frontier in the quest for magnetic fusion energy is the development of a basic understanding of plasma behavior in the regime of strong self-heating, the burning plasma regime.

C. Frontier Physics Issues in a Burning Plasma: Production of a strongly, self-heated fusion plasma will allow the study of a number of new phenomena depending on the degree of alpha self-heating achieved. These include:

- The effects of energetic, fusion-produced alpha particles on plasma stability and turbulence,
- The strong, non-linear coupling that will occur between fusion alpha particles, the pressure driven current, turbulent transport, MHD stability, and boundary-plasma behavior,
- Stability, control, and propagation of the fusion burn and fusion ignition transient phenomena.

D. Generic Issues in a Tokamak Burning Plasma Experiment: A burning plasma experiment in a tokamak configuration is relevant to other toroidal magnetic configurations. Much of the scientific understanding gained will be transferable. Generic issues include the effect of alpha particles on macroscopic stability and alpha particle losses, RF and neutral beam heating technology, the methods used to handle edge power losses, particle fueling and removal, and the feedback mechanisms needed to control the fusion burn. Equally important, the experience gained in burning plasma diagnostics, essential to obtaining data to advance fusion plasma science, will be highly applicable to burning plasmas in most other magnetic configurations.

E. Advancement of Fusion and Plasma Technology: The achievement of burning plasma conditions will lead to advances in fusion and plasma technology essential to operation of a reactor and in basic materials science. However, a number of important technological and material issues facing a fusion reactor will remain to be addressed.

F. The Need for a New Experiment: Present experiments cannot achieve the conditions necessary for a burning plasma. Therefore, addressing the important scientific issues in the burning plasma regime requires a new experimental facility.

G. Technical Readiness for a Burning Plasma Experiment: The tokamak configuration is scientifically and technically ready for a high gain burning plasma experiment. No other magnetic configuration is sufficiently advanced at this time.

H. Range of Burning Plasma Options: There exists a range of experimental approaches proposed to achieve burning plasma operation from compact, high field, copper magnet devices to large super-conducting magnet devices. These vary widely in overall mission, schedule and cost.

I. Sufficient Information to Proceed to the Next Step: Sufficient scientific information is now in hand to determine the most suitable burning plasma experiment for the U.S. program.

J. Cost of a Burning Plasma Experiment: Approximate construction cost estimates of a burning plasma experiment range from hundreds of millions to several billion dollars. A burning plasma experiment, either a large scale international collaboration or smaller scale experiment solely within the U.S., will require substantial funding - likely costing the U.S. more than $100M per year**.**

K. Importance of the Base Program: A healthy base science and technology program is needed to advance essential scientific and technology issues and to capitalize on advances made with the burning plasma experiment. Thus, a burning plasma experiment must be funded with a significant augmentation of the fusion budget.

L. Desirability of a Multiparty International Experiment: A multiparty international experiment has the potential of lowering the cost per party while retaining full technical benefits, representing a highly leveraged investment. However, the necessary political arrangements and multinational commitments can lead to delays and accumulated costs. In addition, the U.S. national scientific infrastructure benefits more from a burning plasma facility built in the United States.

M. Desirability of Advanced Tokamak Capability: Achieving burning plasma conditions does not require Advanced Tokamak (AT) capability. However, the AT line of research has the potential to significantly increase the economic attractiveness of the tokamak. Therefore, the AT capability is highly desirable.

N. Other Applications of Burning Plasmas: In addition to fusion energy production, there are a number of other potential fusion applications compatible with reduced plasma performance (such as transmutation of nuclear wastes and fusion-fission hybrid reactors) that would benefit from the knowledge gained in a burning plasma experiment.

O. U.S. Collaboration on JET: The JET experiment has the capability to explore alpha particle physics at low gain in regimes relevant to burning plasmas. The U.S. would benefit from collaboration on this experiment.

P. Contributions to Other Fields of Science: The conceptual basis and analytic/computational techniques developed in magnetic fusion research have been productively transferred to space-, astro-, accelerator-, and computational physics. The new regimes accessed in a burning plasma experiment (*e.g.* reconnection in the presence of energetic particles and fusion burn dynamics) will extend these contributions.

On the basis of our analysis and Findings, the panel believes that the scientific information is now in hand to determine the most suitable burning plasma experiment for the U.S. program. This is related to the third charge to the panel in which it was asked how the NSO activity, presently devoted to the pre-conceptual design of FIRE, should be used. A proper answer to this question required the panel to consider the role of the NSO in the larger context of a U.S. plan for burning plasma research. Combining these considerations with our Findings led the panel to make five specific Recommendations to FESAC. These are summarized below.

1. *NOW is the time for the U.S. Fusion Energy Sciences Program to take the steps leading to the expeditious construction of a burning plasma experiment.*

The critical burning plasma science issues have been recognized for nearly two decades. They have been investigated theoretically and in a limited way experimentally. Substantial scientific progress has been made by exploiting the capabilities of existing facilities. However, the U.S. Fusion Science Program now needs a new facility to move forward. Based on our progress to date, the community has in hand a knowledge base sufficient to design a burning plasma experiment and to move on to a new frontier of vigorous experimental fusion science, inaccessible to present machines. In addition to the strong scientific justification for a new facility there is additional motivation because of the public's increasing awareness of the importance of energy to the general well being of the nation and the fact that the solution involves a long-term investment in research.

2. *Funds for a burning plasma experiment should arise as an addition to the base Fusion Energy Sciences budget.*

A burning plasma experiment, either international or solely within the U.S., will require substantial funding - likely more than $100M per year. The largest part of this funding should be provided as an addition to the present fusion budget. It is crucial that funding for the project not be generated at the expense of maintaining a balanced base fusion science and technology program. The present program is positioned to develop key insights and develop new understanding into important unresolved science issues, which will ultimately lead to further improvements in the broad spectrum of magnetic fusion concepts. Premature termination of important components of this program would be shortsighted. It would reduce the discovery of important new plasma science phenomena and deplete the fusion science expertise that will be essential when the new facility comes on line.

3. ***The U.S. Fusion Energy Sciences Program should establish a proactive U.S. plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs, the U.S. should be ready to act and take advantage of it but should not be dependent upon it. The U.S. should implement a plan as follows to proceed towards construction of a burning plasma experiment:***

- Hold a "Snowmass" workshop in the summer 2002, for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the workshop should determine which of the specific burning plasma options are technically viable but should not select among them. The workshop would further confirm that a critical mass of fusion scientists believe that *the time to proceed is now* and not some undefined time in the future.

- Carry out a uniform technical assessment led by the NSO program of each of the burning plasma experimental options for input into the Snowmass summer study.

- Request the Director of the Office of Energy Sciences to charge FESAC with the mission of forming an "action" panel in Spring 2002, to select among the technically viable burning plasma experimental options. The selected option should be communicated to the Director of the Office of Science by January 2003.

- Initiate a review by a National Research Council panel in Spring 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by Fall 2003. This is consistent with the submission of a report by DOE to congress no later than July 2004.

- Initiate an outreach effort coordinated by FESAC (or an ad-hoc body) to establish an appreciation and support for a burning plasma experiment from science and energy policy makers, the broader scientific community, environmentalists and the general public. This effort should begin now.

4. ***The NSO program should be expanded both financially and technically in order to organize the preparation of a uniform technical assessment for each of the burning plasma***

options, ITER-FEAT, IGNITOR, and FIRE, for presentation at the Snowmass summer study.

- The mission, goals, science, engineering, cost, and time schedule for each option should be included in the technical assessments. This would require a major involvement of the existing, already funded, fusion community as well as the allocation of approximately $1M - $2M for new work required during the year. The assessments would be organized and led as part of the NSO program.

- The development of the uniform technical assessments requires close interaction between the NSO program and the physics and engineering design teams for the burning plasma experiment options. This is straightforward for FIRE but will require special efforts with respect to interactions with IGNITOR and ITER-FEAT.

- The NSO program is currently focused primarily on a pre-conceptual design of the FIRE experiment and this work should continue unabated.

- For ITER-FEAT and IGNITOR there is considerable information available to prepare the technical assessment. Thus, the NSO activity will largely, but not exclusively, be focused on organizing the material in a form appropriate for the Snowmass meeting.

5. *The U.S. needs to engage the international community in some appropriate capacity with respect to ITER-FEAT and IGNITOR so that these experiments, along with FIRE, can be evaluated on a level playing field.*

Whereas two of the burning plasma experiments under consideration (ITER-FEAT and IGNITOR) are being pursued outside the U.S., we recommend that DOE engage the respective parties to facilitate the technical interaction needed for U.S. planning, begin informal discussions on possible U.S. involvement in those efforts, and establish the groundwork for productive collaborations among burning plasma efforts.

In summary, the panel believes that understanding a burning plasmas would be an immense physics accomplishment of wide scientific significance and would be a huge step toward the development of fusion energy. As a result the panel has suggested a course of action to enable us to present an optimal burning plasma experimental plan to the nation no later that July 2004.

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I. Introduction – Defining the Context of a Burning Plasma Experiment

A. Goals of the Report

The next frontier in the quest for magnetic fusion energy is the development of a basic understanding of plasma behavior in the regime of strong self-heating, the so called "burning plasma" regime. The general consensus in the fusion community is that the exploration of this frontier requires a new, relatively large experimental facility - a burning plasma experiment. The motivation, justification, and steps required to build such a facility are the primary focus of our report.

The specific goals of the report are as follows. First, the report describes the critical scientific and engineering phenomena that are expected to arise for the first time, or else in a strongly modified form, in a burning plasma. Second, the report shows that the capabilities of existing experiments are inadequate to investigate these phenomena, thereby providing a major justification for a new facility. Third, the report compares the features and predicted performance of the three major next generation burning plasma experiments under current consideration (ITER-FEAT, FIRE, and IGNITOR), which are aimed at addressing these problems. Deliberately, no selection of the best option is made or attempted since such a decision involves complex scientific and cost issues that are beyond the scope of the present panel report. Fourth, the report makes specific recommendations regarding a process to move the burning plasma program forward, including a procedure for choosing the best option and the future activities of the Next Step Option (NSO) program. Fifth, the report attempts to provide a proper perspective for the role of burning plasmas with respect to the overall U.S. fusion program. The introduction below provides the basic background information required for understanding the context in which the U.S. fusion community thinks about burning plasma issues. It "sets the stage" for the remainder of the report.

B. Fusion as a Source of Electricity

Generation of electricity by magnetic fusion has proven to be one of the grand challenges of physics and engineering. The problems have been and continue to be, many in number and difficult in solution but one by one they are being solved. Even after many years of struggle the original dream of fusion energy remains as enticing, attractive, and valid as ever.

Magnetic fusion generation of electrical energy is one of the few options that provide a sustainable and affordable energy source with significant environmental and safety benefits for the end of this century and beyond. In fusion the principal fuels, deuterium and tritium undergo a sequence of nuclear reactions whose primary waste product is helium, a well-known and harmless gas. There are no greenhouse gasses or air pollution emissions. The fuels are widely available and plentiful assuring a virtually inexhaustible availability to all nations. (Note that in a fusion reactor a long-term tritium supply will be obtained by in-situ breeding from lithium, a relatively plentiful element.) In terms of safety, even in the worst case accident there would be no technical reason for evacuation of the nearby population. Finally, fusion fits into the existing economic infrastructure. A typical reactor size of *1-2 GWe* is comparable with generation capabilities at present sites and can use existing transmission lines. It does not need the extensive pipeline or liquefaction facilities that natural gas requires.

While the helium waste of the fusion burning process is harmless, the nuclear reactions of the fusion process do produce a secondary source of waste, the activation of structural material comprising the reactor core. Fortunately, this material can be chosen so as to minimize long-term radioactive waste hazards. After *100 years*, a fusion reactor constructed of vanadium has a radiological hazard potential *5* orders of magnitude below that of a comparable fission reactor. The activated material would then qualify for shallow waste burial. Also, while care is required handling the radioactive tritium in the fuel, it has a half-life of only *12 years* and as a radioactive material it is relatively non-toxic. Thus tritium represents a minimal hazard to the public.

Enormous scientific and technological progress has been made in fusion research since the late 1960's. Difficult problems remain but there is high confidence, backed by a strong track record, that these problems will also be solved. The ultimate challenge for the fusion community, one that will determine the rate at which fusion energy contributes to the world energy supply, is that of developing scientific and engineering solutions whose reactor embodiment leads to an economically attractive source of energy - one characterized by a competitive cost-of-electricity, high reliability, high availability, and easy maintainability.

It is also worth noting that in addition to direct electrical energy production, a fusion energy source can be applied in essential ways to a near term fission economy. The plasma performance requirements for such applications can be substantially reduced from those required for the direct production of electricity from fusion. As examples, fusion sources can produce a steady copious supply of neutrons that may be able to de-nature the long term radioactive toxicity of fission produced waste, or to breed U-233 from thorium, in order to enable a fission cycle that would be free from diversion of fuel for nuclear weapons. Another application of fusion involves the co-production of hydrogen with electricity during off-peak hours. This would balance the load on the fusion plant and demonstrate the possibility of fusion energy becoming a source of prime energy in the transportation sector as well as in electricity production.

In summary, the next step on the path to fusion energy is a burning plasma experiment. This report addresses the issue of the technical readiness for such a step and recommends a procedure for moving forward.

C. Definition of a Burning Plasma

As a starting point a definition is given of precisely what is meant by a "burning plasma." The primary assumption is that the plasmas of interest consist of a *50% - 50%* mixture of deuterium and tritium. The corresponding D-T fusion reaction is given by

$$D + T \rightarrow \alpha(3.5\ MeV) + n(14.1\ MeV)$$

The fusion neutrons are not confined by the magnetic field and escape the plasma region. It is primarily their kinetic energy that is ultimately transformed into heat in the surrounding blanket and then converted to electricity. The fusion α particles are electrically charged and remain confined within the plasma by the magnetic field. They transfer their kinetic energy to the plasma through collisions, thereby replenishing some of the energy constantly being lost through heat conduction, the primary energy loss mechanism. It is the fraction of heat conduction loss that is replaced by fusion α particles as compared to that replaced by externally applied heating power that determines whether or not a plasma is a "burning plasma." Specifically, in steady state plasma losses, P_l, must be balanced by the sum of α power, P_α, and externally supplied heating power, P_{ext}: $P_l = P_\alpha + P_{ext}$. Note that P_{ext} itself is comprised of two contributions: $P_{ext} = P_{aux} + P_{ohm}$ where P_{aux} is the auxiliary power supplied by purely external sources (e.g. RF power) and P_{ohm} is the ohmic power dissipated by the plasma current. When the ratio

$$f_\alpha \equiv P_\alpha / (P_{ext} + P_\alpha) = 1/2$$

then α heating equals external heating. This is the transition point into the burning plasma regime.

A realistic burning plasma experiment by definition must be dominated by α heating. Such an experiment would thus be characterized by a value of f_α substantially above threshold, say $f_\alpha \approx 2/3$, corresponding to an α power equal to twice the external power. A fully ignited plasma, which requires no external heating, would be characterized by $f_\alpha \approx 1$. The best D-T performance to date has occurred on the European experiment JET, which has achieved $f_\alpha \approx 0.15$ during transient periods. On long pulse discharges on JET and on Princeton Plasma Physics Laboratory's TFTR experiment, sustained values of $f_\alpha \approx 0.04$ have been achieved. Note that the total fusion energy per D-T reaction (i.e. alphas plus neutrons) is approximately five times larger than the α energy alone. Consequently, a burning plasma experiment with $f_\alpha \approx 2/3$ produces a thermal fusion power that is ten times greater than the external power necessary to maintain the plasma

$$Q \equiv (P_\alpha + P_{neutron}) / P_{ext} \approx 10$$

D. Major Issues in a Burning Plasma Experiment

The burning plasma regime is a critically important regime of plasma physics to investigate. As already stated, it is the next step forward in terms of scientific performance on the path to fusion energy, one that has yet to be investigated. The extrapolation of present non-burning performance to the burning plasma regime is non-trivial. Present experiments are characterized by a substantial amount of external control of current and pressure profiles by means of auxiliary RF power and neutral beams. Profiles can thus be optimized to yield maximum performance. In the burning plasma regime the self-heating due to α particles is so large that the control flexibility associated with external heating sources is dramatically reduced. Consequently, it is of primary importance to understand plasma behavior in this new regime of operation in order to predict performance in reactor grade plasmas and to have a facility on which scientists can discover new methods of optimization.

In terms of experimental capabilities there are two primary issues, high performance and long pulse operation. It will be a truly major scientific milestone along the path to fusion energy to build an experiment that produces substantially more fusion power than it consumes. This will require the production of high performance plasmas characterized by high temperatures, high densities, good macroscopic stability, and good confinement of the plasma energy. To accomplish these goals a burning plasma experiment must possess the hardware capabilities to provide: (1) some level of profile control, (2) stabilization of macroscopic plasma instabilities, and (3) robust plasma-wall facing components that can withstand high heat and neutron wall loadings. Furthermore, this performance must be sustained over a reasonably long period of time.

This leads to the next requirement in a burning plasma experiment, pulse length. There are several different experimental time scales that occur in high performance plasma discharges. These involve the energy loss rate of the background plasma, the energy transfer rate from the alphas to the plasma, the particle accumulation rate of cooled down α particles, and the current redistribution time, which is closely related to the *"L/R"* resistive equilibration rate of the plasma. The current redistribution time (τ_{CR}) is usually the longest, on the order of many seconds or even minutes in some cases. Pulse lengths (τ_{pulse}) on existing experiments are usually much less than the skin time $(\tau_{pulse} << \tau_{CR})$ and thus profiles are not fully equilibrated at the end of the discharge - there is still transient evolution. Ultimately a burning plasma experiment must be designed with sufficient pulse length $(\tau_{pulse} >> \tau_{CR})$ to enable the investigation of the long-time evolution of current and pressure profiles in the presence of strong α heating. Only then can one be confident about the achievement of true "steady state" operation. However, pulse length directly impacts the cost of an experiment. It may thus make fiscal sense that the first experiments designed to achieve strong self-heating will do so in facilities that sacrifice some degree of long pulse operation; that is, they may be designed to achieve $\tau_{pulse} \sim \tau_{CR}$. Later experimental upgrades, or perhaps new facilities, will be needed to address the vital issues associated with the long-time evolution of the current and pressure profiles.

The achievement of reasonably sustained high performance plasmas in the presence of large self-heating is the major scientific mission of a burning plasma experiment.

E. Near Term Burning Plasma Experiments

Tokamak Configurations: The Clear Choice

All fusion scientists agree that a burning plasma experiment will be needed at some point along the path to fusion energy. However, the context of the present report is focused on the technical issues and motivation for such an experiment in the near term - design and the beginning of construction within the next several years. The short-term focus implies that the magnetic fusion concept of primary interest is the tokamak. This particular configuration is the one most studied in the U.S. and international fusion programs and has demonstrated the most promising performance to date. It is the clear leader in the field and is thus the obvious choice for a near term burning plasma experiment. In terms of other options, the stellarator is a different magnetic configuration showing promise but still has not as yet achieved confinement comparable to that in a tokamak. Hence, a burning plasma experiment based on this concept is premature at the present time. The spherical torus concept also shows promise but is a less advanced idea and a more extensive physics database on existing experiments is required before proceeding to a burning plasma class experiment. Other alternate concepts within the broad U.S. fusion program need to demonstrate substantial improvements in their confinement characteristics before they can be considered as candidates for a burning plasma experiment.

A Broad Range of Design Possibilities

Another important point with regard to the context of a burning plasma experiment is its role within the international fusion program. Fusion is truly an international endeavor and there may be opportunities for the U.S. to participate as a collaborator on one of several major devices under consideration. For example, at present there exists an international collaboration involving Japan, Europe, and Russia, focused on a reduced version of the original International Thermonuclear Experimental Reactor (ITER) design, now called ITER-FEAT, but the U.S. is not currently involved in this activity. Similarly, there has been a long ongoing effort to build a compact, low cost ignition device in Italy called IGNITOR. Although the scientific leader of this project is a U.S. scientist, the U.S. has no formal participation in the IGNITOR program. Finally, there is a substantial U.S. effort to design a facility intermediate in size between IGNITOR and ITER. This experiment is called the Fusion Ignition Research Experiment (FIRE) and under certain conditions may have the potential to attract international collaboration. There has also been a recent European recommendation to carry out a study of a copper coil tokamak for a burning plasma experiment. In summary, these experiments offer a wide range of design options in terms of mission, cost and timing.

Prospects for International Collaboration

To the extent that a near term burning plasma experiment is determined to be a desirable goal, the U.S. must consider its options. Under what conditions should the U.S.: (1) rejoin the ITER effort, (2) take a leadership role in developing FIRE in a national or international context, or (3) attempt to participate in the IGNITOR project. This involves both scientific and political issues. The present report considers only the scientific issues. A word of caution, however, is warranted at this point. It would probably be a mistake for the U.S. to adopt as its primary strategy a “wait and see” policy with respect to international collaborations. The U.S. needs to develop its own program and not rely too heavily on international collaborations. If and when opportunities arise, the U.S. can modify its strategy as necessary.

F. Organization of the Report

The remainder of the report is organized as follows. The first topic discussed in Section II is a description of a tokamak. The purpose is to help the reader understand the basic components comprising a tokamak. Knowledge of tokamak operation is essential in order to understand the science and engineering problems that need to be addressed in a burning plasma experiment. Next, Section III presents an overview of the main scientific issues expected to arise on the burning plasma frontier. This overview is important in defining the basic scientific mission of the experiment. With the mission in hand, Section IV attempts to compare the desired scientific requirements with the capabilities of the three proposed burning plasma experiments as well as with existing facilities. The goal is to determine the strength of the justification for a new burning plasma experiment. The results of the panel's deliberations are summarized as a series of "findings" in Section V. Lastly, Section VI contains a set of specific recommendations to FESAC describing in detail how the U.S. should proceed with its program.

G. The Main Conclusion

The U.S. fusion program, and indeed the world fusion program, is technically and scientifically ready to proceed NOW with a burning plasma experiment.

This is the logical next step on the path to fusion energy. The key physics and engineering questions have been known since the mid 1980's. They have been investigated theoretically during the interim period. They have been investigated on existing experiments, although often one at a time or in reduced performance regimes because of experimental limitations. Further progress requires a new, large scale burning plasma experiment. Thus, the key question is not "Are we ready?" but instead "How should we proceed?"

Over the years there have been many proposals for burning plasma experiments, some of them quite detailed and extensive in content. These designs have been continually evolving and at present there are three serious contenders actively under consideration in the U.S. and world community: ITER-FEAT, FIRE, and IGNITOR. The designs cover a wide range of missions, a wide range of costs, and a wide range of time scales. Consequently, the panel feels that the community's efforts would be best spent improving and refining these designs, subjecting them to the highest level of scrutiny, rather than developing additional pre-conceptual designs. This would insure that if any of these devices were built, it would be successful in carrying out its mission. The panel believes, in fact, that construction of any of the options would represent a major step forward in the fusion program.

How should the U.S. proceed? The panel has reached consensus on a number of major points related to this question. The points are described below and later formulated in a series of specific recommendations in Sec.VI. First, the U.S. must become engaged in both the ITER-FEAT and IGNITOR projects or else we will have illogically eliminated possible burning plasma options. Second, the U.S. fusion community needs to evaluate each of the three options in a uniform manner with respect to mission, probability of success, cost and timing. Third, asking "Which is better, ITER-FEAT, FIRE, or IGNITOR?" is the wrong question. Each has a distinctly different mission and a very different cost and time scale. The question that the community should address is which of these options represents a technically viable design; that is, the community must insure that each proposal is held to the highest standards to insure success if chosen. Fourth, it is unlikely that the community, solely by itself, will be able to select one of the three options. Each option will have a sufficient number of supporters to preclude even a simple majority choice. Fifth, a high-level panel must make the single selection decision with input from DOE, OMB, Congress, and possible international partners. There are important political and financial issues to consider and the final choice will not be made on the basis of science alone. However, once the selection is made, the fusion community must be ready to back the choice wholeheartedly. Sixth, wholehearted endorsement of a single burning plasma experiment is essential in order for the fusion community to present a unified, convincing and credible case to our scientific colleagues in other fields, the DOE, OMB, and Congress, all of whose support we need to obtain new funding for such a facility. Seventh, the panel believes the selection decision can be made by 2004 in time for a burning plasma assessment called for in the FESAC Priorities and Balance Report.

II. Simple Description of a Tokamak

In order to understand the science and engineering issues facing a burning plasma experiment, it is useful to begin with a brief description of a tokamak. Of interest are the various components that comprise the device and their purposes. Also presented is a qualitative description of two different regimes of tokamak operation, the choice of which has a large impact on the design of a burning plasma experiment. These regimes correspond to “standard tokamak” operation and “advanced tokamak” operation.

A. Components of a Tokamak

A tokamak is an axisymmetric toroidal plasma confinement device. The main components relevant to a burning plasma experiment are the magnet system, the external heating and current drive system, and the divertor system. A simple schematic diagram is illustrated in Fig. 1. The geometry is shown in Fig. 2.

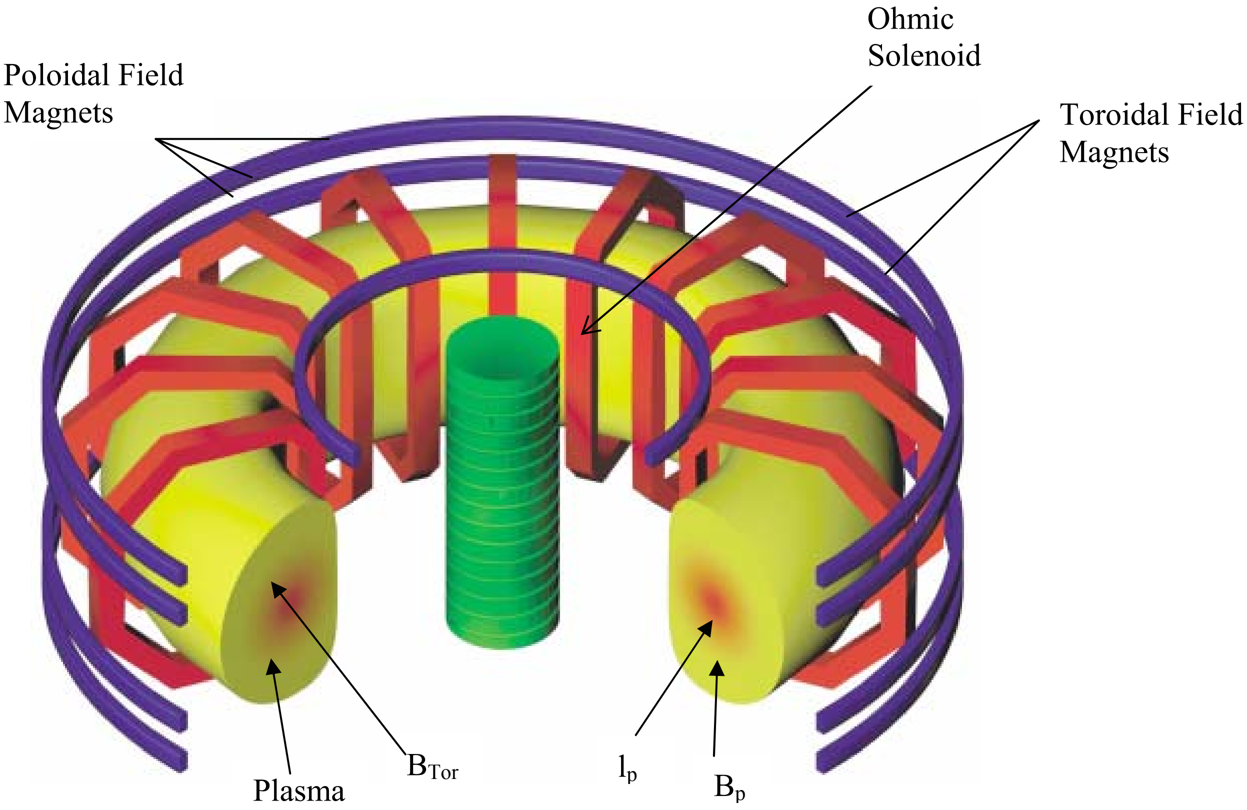

Fig. 1 Schematic diagram of a tokamak

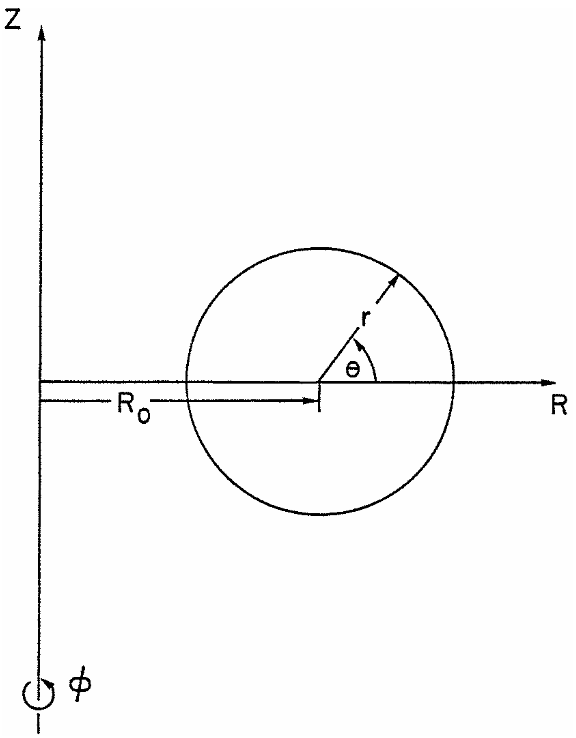

Fig. 2 Geometry of a tokamak

Consider first the magnet system, which consists of three sub-systems: the toroidal field magnet, the ohmic transformer, and the equilibrium field magnets. The dominant magnetic field is produced by the toroidal field coils. This field is required to maintain macroscopic stability of the plasma and to provide partial confinement against the outward radial (along r) expansion forces. The ohmic transformer is a central solenoidal coil whose primary purpose is to drive toroidal current in the plasma. This occurs by ramping the current in the coil monotonically in time, thereby inducing a toroidal DC electric field in the plasma, which then acts as the secondary of the transformer. The plasma current also provides partial confinement against the radial expansion forces. The equilibrium field coils have two functions. First, they provide an inward restoring force (along R) to balance the outward forces inherent in any toroidally symmetric magnetic geometry containing a toroidal current. Second, they provide the necessary poloidal fields to generate the desired plasma shape. For example, elongated and triangular "D" shaped plasmas have superior performance compared to a simple circular cross section.

The external heating system in the plasma consists of various high frequency RF power supplies, high power neutral beams or a combination thereof. These external sources are required to raise the plasma temperature to a sufficiently high level (i.e. greater than *10 keV*) to initiate a large number of fusion reactions and the accompanying production of α particles. The plasma heating due purely to the transformer induced ohmic dissipation is not sufficient to reach the desired temperatures.

A related external system is the current drive system whose purpose is as follows.

As is well known a transformer can only induce a DC secondary current for a finite time. For the long pulse, perhaps even steady state operation ultimately desired in the burning plasma regime, a method is required that sustains the current once the volt-seconds of the transformer have been consumed. One such method is as follows. An electromagnetic wave traveling in one direction around the torus drags electrons with it producing a non-inductively driven current that can in principle be sustained indefinitely. Another method involves the unidirectional injection of toroidally tangential neutral beams. Under certain conditions the beam momentum can be used to drive a steady state toroidal current.

Tokamaks have traditionally used divertor and limiter configurations to control plasma edge properties. It is here that the plasma first comes into contact with a solid wall. In recent tokamak experiments and most proposed new tokamak experiments, a divertor is the usual choice of plasma-boundary interface (with IGNITOR a notable exception). The key feature of a divertor is a null point in the poloidal magnetic field. In contrast a limiter configuration generally consists of a metallic ring or series of such rings directly in contact with the plasma and without a null point in the poloidal field. A limiter has the advantage of requiring a much smaller volume between the plasma and the wall. Although this potentially leads to a substantial saving with respect to size and cost many would, nevertheless, argue that a limiter is not as effective as a divertor in handling impurities. On the other hand, limiter proponents argue that the problem is greatly alleviated when operating at high densities. ITER-FEAT and FIRE make use of a divertor while IGNITOR essentially uses the entire first wall as a limiter surface.

Consider first the divertor. The null point in the magnetic field is created by appropriately locating and adjusting the current in certain of the equilibrium field coils. The open field lines outside the separatrix surface allow particles at the edge of the plasma to flow freely and make first contact with a solid surface, the metallic divertor surface, at a substantial distance from the plasma core. This large separation, not present with a limiter, greatly reduces the influx of impurities back into the plasma, a desirable property in a burning plasma experiment. Otherwise, impurity radiation in the plasma core would cause significant power loss that would lower the plasma temperature. In addition, the presence of ionized impurities in the core would dilute the fusion D-T fuel. Both of these effects result in a reduction of the number of fusion reactions taking place; that is, f_α is reduced. A further advantage of the divertor is its ability to help remove the αs after they have given up their energy to the plasma. Unless this “helium ash” is removed, the concentration of fusion producing D-T fuel will become progressively more dilute, reducing the fusion power output. This problem becomes important when the helium ash diffusion time is shorter than the pulse length. Note that in this regime, a limiter plasma faces a more difficult problem than one with a divertor and would need extensive pumping to prevent degradation of the burn. On the other hand, a difficulty with the divertor is that the heat load on the divertor surface is potentially very large because of heat focusing on a relatively small surface area. Handling this heat over long periods of time is a major engineering challenge.

An alternate method of plasma edge handling is to spread the heat load over a much wider area of contact surface by using either metallic rings (i.e. a limiter) or even the entire plasma facing wall itself. The latter is the solution being proposed in the IGNITOR design. In a high magnetic field high density discharges, using either a limiter or the plasma-facing first wall to extract the heat loss, it has been shown by empirical measurements that the fractional impurity level percentages are less than in plasmas at more conventional densities. It may also be possible to achieve a “radiative mantel” condition at the edge, where the edge plasma cools to a sufficient level to recombine and radiate away most of its thermal energy.

B. Standard vs. Advanced Operation

The final topic in this section concerns the qualitative differences between standard and advanced tokamak operation. These differences can be most easily understood in terms of two dimensionless physics quantities. The first of these is β which represents the ratio of plasma pressure to magnetic pressure: $\beta \equiv p / (B^2/2\mu_0)$. The parameter β is a measure of the efficiency of the magnetic field to confine plasma. The second quantity is known as the “bootstrap” fraction f_B whose significance is as follows.

In a toroidal tokamak as particles diffuse radially outward (along r), their transport induces a toroidal current in the plasma known as the bootstrap current. This current, if properly aligned, can provide some or most of the poloidal magnetic field required for steady state operation. The bootstrap current, thereby, reduces the amount of external auxiliary current drive power required to maintain a steady state plasma. Reducing this power is an important goal since in a reactor it is necessary to keep the steady state recirculating power fraction at an economically low value. The fraction of the total toroidal current provided by the bootstrap effect is denoted by f_B: $f_B \equiv I_{bootstrap}/I_{total}$. The parameter f_B plays an important role in the overall economics of the concept.

Standard tokamak operation is the easier regime to achieve experimentally. Less external profile control is required and the plasma behavior is relatively robust. The difficulty with standard operation is that the achievable β and f_B values are not sufficiently high to meet the technological and economic constraints required in a steady state superconducting power reactor, at least as currently envisaged. The values are, however, high enough to achieve strong self-heated operation in the burning plasma regime. Low values of β ultimately result in high capital costs in a reactor since large devices are required to produce a given amount of power. Similarly, low values of f_B lead to large values of current drive power corresponding to high recirculating power. This is an unsatisfactory economic situation since RF or neutral beam power is relatively expensive and inefficient compared to a conventional transformer drive (and indeed too large an auxiliary current drive requirement can prevent efficient net energy extraction for a future fusion power plant). Considering the option of a pulsed, rather than steady state, reactor can alleviate low values of f_B.

Advanced tokamak operation is based on a relatively recently discovered regime of operation. It requires a more careful programming of the time history of the toroidal current as well as the current and pressure profiles. It is not, at least presently, as robust a regime of operation as standard operation. The main characteristics of advanced operation are the simultaneous achievement of higher values of β and f_B and imply a correspondingly higher value of background plasma confinement time. Although the advanced regime is less studied, the higher values of β and f_B extrapolate more favorably into the reactor regime under the assumption that alpha particle physics remain the same in both modes of operation. Whether or not this is indeed true is one of the important areas of investigation in a burning plasma experiment. The decision as to whether or not a burning plasma experiment should have an advanced operational capability involves tradeoffs. Potentially improved physics performance with a favorable extrapolation to the reactor regime must be weighed against the higher costs of including such capabilities.

The above discussion describes standard and advanced operation as two distinctly different modes of operation. The sharp distinction is helpful in visualizing both ends of the spectrum. In the reality of experimental plasma physics, however, there is actually a continuum of operation. The minimum values of β and f_B that are ultimately required in a tokamak power reactor might well lie intermediate between the extremes. In terms of a burning plasma experiment, it would thus be highly desirable for the design to have the flexibility of incorporating advanced operational capabilities as well as possible new ideas at later stages of experimentation.

III. The New Science of Burning Plasmas

As has been stated, a burning plasma is the next step along the path to fusion energy and understanding the physics of such plasmas is clearly crucial in order to successfully proceed along this path. What should not be underestimated, however, is that in addition to its energy goals, the new physics of burning plasmas is remarkably fascinating and exciting in its own right. It is a major grand challenge in the physical sciences.

Section III describes the most important new science issues that need to be addressed in a burning plasma experiment. In an approximate sense they divide into two categories. The first involves modifications, often large, of phenomena present without α particles that may be positively or negatively impacted under burning plasma conditions; that is, how does the plasma behave when subjected to a new large heating source whose deposition profile is determined by the internal properties of the plasma. The second involves wholly new phenomena resulting directly from the presence of α particles. For instance, will the presence of a large population of α particles generate new microscopic instabilities that cause an anomalously fast loss of these same α particles, thereby reducing both the plasma temperature and fusion gain?

The material describing the science issues comprises a substantial portion of the report and is described below. This information represents the primary input into the panel's conclusion regarding the justification for a burning plasma experiment. Of particular interest is the importance of synergy. Specifically, how important is it to have a new single facility that can address the multiple, nonlinear interactions of the various burning plasma phenomena simultaneously versus testing the phenomena separately, probably at a reduced level, on existing (plus modifications) facilities? The latter approach would likely be less expensive in the short term but would not include the crucial synergistic interactions.

In beginning the discussion it is worth noting that there is a strong consensus within the fusion community concerning the identification of the general science issues inherent in any magnetic fusion concept. These issues include macroscopic equilibrium and stability of the plasma, heating and current drive, energy and particle transport, and plasma-boundary interactions. Access to the burning plasma regime also introduces the possibility of new phenomena associated solely with the presence of a large number of α particles. A final important issue for a burning plasma experiment is pulse length which, in appropriate dimensionless units, must be extended over that achieved in most existing experiments. The critical time scales are the pulse length of the burn τ_{pulse} and the current redistribution time due to plasma resistance τ_{CR}. Achieving a burn duration, $\tau_{pulse} \geq \tau_{CR}$ represents an important step towards establishing the viability of long pulse or ultimate steady state operation with a tokamak. A summary of the major issues and corresponding critical physics parameters characterizing a burning plasma experiment is given below.

A. Macroscopic Equilibrium and Stability

Macroscopic equilibrium and stability behavior is concerned with discovering optimized magnetic geometries that can confine high values of plasma pressure (i.e. β) in a stable manner. Such behavior is governed by magnetohydrodynamics (MHD). High plasma pressure is required in the burning plasma and reactor regimes. The reason is that at fusion temperatures both the fusion and α power densities are directly proportional to the square of the plasma pressure. Typically, pressures on the order of *10 atm* are required for tokamak burning plasmas and fusion reactors.

There are a number of MHD phenomena that limit the maximum achievable pressure for a given magnetic configuration. These are associated with various MHD instabilities that are triggered when the parameter β exceeds a critical value (i.e. the beta limit). The most dangerous MHD modes lead to a rapid termination of the discharge known as a "disruption." The plasma pressure and toroidal current are quenched on a fast time scale. The transient currents that flow in the vessel walls are sufficiently high that the resulting stresses are literally capable of producing irreversible damage in large experiments. Frequent disruptions in a burning plasma experiment are not an acceptable situation.

In general too much plasma pressure, too much plasma current, or too much plasma density can drive the MHD instabilities that lead to disruptions. Certain disruptions occur even if the plasma is constrained to behave as a perfectly conducting medium. Others occur when the perfect conductivity constraint is relaxed and finite plasma conductivity is allowed. Often a close, perfectly conducting wall surrounding the plasma is predicted to stabilize these dangerous MHD modes. However, the realistic experimental situation corresponds to a finite conductivity of the wall and this again lowers the critical β for disruptions. Lastly, density driven disruptions depend upon the radiation properties of the edge plasma.

In terms of a burning plasma experiment a critical issue is to first define and then simultaneously achieve the desired pressure, current, and density required to accomplish the scientific mission. There is no single choice of desired parameters. Instead, there is a range of options that depend upon the criteria given below, and whose importance depends on the weight of plasma physics vs. reactor relevance. Each one of the criteria will be used in Section IV to compare, in the context of a cost-benefit analysis, the different proposed burning plasma experiments.

The first criterion is physics based and is related to MHD pressure driven instabilities. Both theory and experiment have shown that the stability limit against the most dangerous classes of MHD modes can be expressed as

$$\beta < \beta_{crit} \equiv \beta_N (I/aB)$$

where I is the toroidal plasma current in *MA*, a is the plasma minor radius in *m*, B is the toroidal magnetic field in *T* at $R = R_0$ and β is measured in *%*. The quantity β_N is a parameter that is determined primarily by the specific shape of the current and pressure profiles, in addition to internal transport behavior and flow dynamics. When $\beta > \beta_{crit}$, dangerous MHD instabilities will be excited leading to degradation of plasma performance or even catastrophic termination of the discharge (i.e. a disruption). The two most severe limitations on β are due to the so-called Neoclassical Tearing Mode (NTM) and the Resistive Wall Mode (RWM). The NTM is excited when $\beta > \beta_{crit}$ corresponding to $\beta_N \approx 2$ while the RWM requires $\beta_N \approx 3$. Promising techniques for suppressing the NTM and RWM are currently under investigation that could open the way to high β operational regimes that are very attractive for a fusion reactor (the so-called advanced tokamak or AT regime).

In terms of reactor relevance it is not β itself that is directly the critical parameter. It is instead the absolute magnitude of the plasma pressure since the fusion power density is proportional to $p^2 \sim \beta^2 B^4$. Power balance and economic considerations indicate that the volume averaged power density of a fusion plasma (alphas plus neutrons) must typically be on the order of $1\ MW/m^3$ in a reactor. This corresponds to a pressure of approximately $p \approx 0.8\ MPa \approx 8\ atm$.

Given the fact that the MHD instabilities can lead to disruptions and prevent access to the burning plasma regime, it is crucial that the plasma beta be maintained at a sufficiently safe value. This should be a strict requirement for a burning plasma experiment in the standard mode of operation. After investigating the burning plasma regime in the standard mode, a burning plasma experiment can test and challenge the higher beta values required in the advanced mode of operation by using active control techniques (current profile control and feedback stabilization) to attempt to suppress the MHD instabilities.

Another limitation imposed by MHD instabilities is on the plasma current. If the plasma current is too large, current driven instabilities known as kink instabilities are excited and the plasma disrupts. The actual stability boundary depends upon the magnitude and radial profiles of the poloidal and toroidal magnetic fields, the pressure profile, and the geometry of the cross section (e.g. elongation, triangularity, and aspect ratio). A simplified approximate form for this complicated stability boundary can be expressed in terms of the parameter $q^* = 5\ a^2 B\kappa/R\ I$ where κ is the plasma elongation (usually in the range $1.5\text{-}2$ in most tokamaks). The quantity q^* is known as the kink safety factor. It is inversly proportional to the plasma current I and is a measure of the pitch angle of the magnetic field lines. Typically, current driven disruptions are avoided when

$$q^* > 1.5$$

However, due to other MHD considerations the limitation on q^* is often somewhat higher than this value as discussed next.

Sawtooth oscillations are another MHD instability that may pose a serious threat to the onset of the burn wave. Sawteeth are internal relaxations of the plasma leading to a flattening of the temperature profile within a central region of the plasma column. When operating in the standard mode, a tokamak plasma always develops a sawtooth unstable region at one point or another during the discharge. Depending on the size of the unstable region, the magnitude of the temperature collapse, and the impact on the alpha particle population, sawteeth could have the benign effect of controlling the burn. However, they may also quench the burn or even worse they may seed other instabilities leading to plasma disruptions. It is prudent to approach the burning plasma regime by reducing to a minimum the size of the unstable sawtooth region. This can be accomplished as follows. Typically, the size of the unstable region, in analogy with current driven disruptions, depends upon the profiles and cross sectional geometry. Larger q^*, lower β, peaked profiles, and high elongation tend to reduce the size of the unstable region. A detailed numerical analysis is needed to determine acceptable values of q^* and profiles. Past experience with such analysis has shown that a burning plasma should operate approximately with

$$q^* > G(\varepsilon, \kappa, \delta, \beta)$$

to limit the size of the unstable region and the impact of sawteeth. Here, G is a numerically computed function of the inverse aspect ratio ε, the elongation κ, the triangularity δ, and the plasma beta. For the three experiments under consideration the values of G are given by $G = 1.5$ for IGNITOR, $G = 2$ for ITER-FEAT, and $G = 2$ for FIRE.

The last criterion of interest corresponds to the density limit. It has been found empirically that tokamak plasmas will disrupt when the density exceeds a critical value denoted by n_G. Furthermore the energy confinement deteriorates even when operating near the critical density. In spite of the attractiveness of operating at higher densities and lower temperatures, a burning plasma experiment must operate with

$$n < n_G \equiv I/\pi a^2$$

Here n is the number density measured in units of 10^{20} $particles/m^3$. As before, I is measured in MA and a in meters. It is worth noting that some recent experiments utilizing advances in inside pellet launch have attained favorable H-mode confinement during transient periods at densities $n \approx 1.5 n_G$. Thus, while there will be a density limit in a BPX, the precise numerical value is only approximate and not a “hard” limit. It is an important element of burning plasma science to establish the physics processes governing the operational densities that tokamaks can achieve.

The expected values of the quantities β_N, p, q^*, and n/n_G are important measures of the performance of a burning plasma experiment with respect to MHD instability disruptions.

B. Heating, Fueling, Rotation, and Current Drive

A burning plasma experiment (BPX) can be optimized both for scientific productivity and fusion energy performance using external sources of energy, particles, angular momentum, and electromotive force - otherwise known as heating, fueling, rotation drive, and current drive, respectively. These sources are used in present experiments to modify the magnitudes and profile shapes of major plasma parameters, including density, temperature, and current, and this capability will be important in a BPX.

Once-heated into the burning plasma regime, a long pulse ($\tau_{pulse} > \tau_{CR}$) or steady-state BPX will develop its own internal heating source and pressure gradient from the self-heating, and be subject to instability drives from the alpha particles generated from the fusion reactions. After the volt-seconds of the ohmic transformer have been consumed, there will be natural toroidal current density profiles associated solely with the bootstrap current driven by the radial pressure gradient. These self-consistent natural profiles are not yet known from present experiments. External control and optimization will be particularly important if the profiles are either suboptimal thereby inhibiting the burn, or alternatively cause overheating of the core accompanied by a thermal run-away instability. In either event, control and optimization will be carried out in the context of these profiles.

Even in the absence of the need to optimize the burn, external controls are an essential part of the study of transport and other important physics. As an example, in present day advanced tokamak experiments external controls are used to change the shape of the current profile to enhance magnetic shear stabilization of the electrostatic turbulence which drives energy transport, resulting both in a deeper understanding of the turbulent processes and enhancing energy confinement.

This section presents a brief description of the tools involved, their scientific basis, and their limitations - not all tools are compatible with a specific burning plasma scenario. It is important that the overall auxiliary power requirements for these external control tools be kept small since the corresponding experimental equipment is quite expensive per watt. As a result, the leverage required for their use effectively requires a thorough understanding of the physics of their interaction with the plasma. A firm basis for this understanding exists from present experiments and theory, and will undoubtedly be improved as a BPX is brought into burning operation.

Contemporary plasma experiments have demonstrated the ability to raise plasma temperatures by external means from initial values of *1-2 keV*, characteristic of the ohmic heating associated with dissipation of the plasma current, into the range $T \sim 10\text{-}20\ keV$ - comparable to temperatures anticipated in fusion reactor cores. These experiments culminated in the successful generation of fusion power by deuterium-tritium plasmas at the predicted levels in TFTR and JET, including direct detection of fusion α-particles. However, the TFTR/JET plasma discharge conditions characterized by $T_i >> T_e$ were optimized to maximize fusion production in this regime by methods that cannot be directly generalized to a burning plasma scale device where one expects $T_i \approx T_e$. Moreover, the fusion power generation remained far short (by about a factor of 10) of that required to maintain the plasma temperature by self-heating with fusion α-particles. Nonetheless, our ability to predict the observed level of fusion power in these devices provides strong support for our confidence in our ability to design a burning plasma experiment.

Before beginning the detailed discussion, there is one point of strategy concerning the external power supplies that should be made. The point is that for a BPX, a key decision issue is its cost. Staged introduction of heating and current drive systems constitute one effective way to minimize the initial cost. The key design challenge is to assure that the design does not preclude future upgrade capabilities. For example, in a superconducting tokamak, steady-state operation of a burning plasma facility can be assured even if the initial experiment is capable only of finite length pulses. Another example is the nuclear blanket testing phase, where core plasma fusion rates and neutron fluxes could be maintained by high auxiliary core heating - up to 100 MW of gyrotron Electron Cyclotron Heating (ECH) - to provide required neutron fluences in the event of shortfalls in confinement performance. This ugrade flexibility has been designed into the ITER-FEAT BPX.

The ITER-FEAT strategy of utilizing superconducting magnets with considerable design flexibility for heating and current drive upgrades needs to be ultimately judged on a cost-benefit basis with respect to the copper magnet designs of FIRE and IGNITOR. Here too it makes sense to design in flexibility with respect to heating and current drive upgrades. However, relative to ITER-FEAT, the FIRE and IGNITOR designs can only be upgraded to a limited extent with respect to very long pulse or steady state operation because of ohmic overheating in the toroidal field coils. Nevertheless, their compact size and use of copper magnets leads to a lower initial cost than ITER-FEAT, even before upgrades.

The various auxiliary power and fueling methods currently available bring considerable capability and flexibility to a burning plasma experimental facility, as discussed below.

Neutral Beam Injection (NBI) has been the workhorse of the tokamak program. It supplies heat, particles, current-drive, and angular momentum in known ratios. NBI access requirements limit its use among the three BPX candidates to ITER-FEAT scenarios. Penetration to the plasma center in ITER-FEAT calls for beam energies E_b in the range $0.5 < E_b < 1.0\ MeV$. This energy requires a negative-ion NBI development program, which is in place in Europe and Japan. One could also consider conventional, positive ion neutral beams ($E_b \approx 0.1\ MeV$) with partial penetration to supply angular momentum to ITER-FEAT.

Fast-wave ion-cyclotron and electron heating (*50-200 MHz*) is possible for all three BPX scenarios. For example, the IGNITOR and FIRE concepts, as well as the present Alcator C-Mod device, rely on fast wave ion-cyclotron heating, which is compatible with high magnetic field designs. High fields do not in general permit sufficient access for the Neutral Beam Injection (NBI) heating techniques used in the TFTR/JET D-T experiments. The fast-wave technique can generate a population of high-energy minority ions for the study of TAE modes and other energetic particle physics. Central electron heating and current drive is also possible and is a key element of Spherical Torus operations. Angular momentum input is weak but fast waves should drive rotation at diamagnetic velocities. The principal difficulty has been in designing antennas that are free of breakdown.

Electron cyclotron heating and current drive is possible for ITER-FEAT at a frequency of *170 GHz*, but not available at the higher frequencies called for by the higher magnetic fields in FIRE and IGNITOR. Access is excellent and the source can be separated from the plasma. Wave-plasma interactions can be highly localized and suppression of Neoclassical Tearing Modes by electron cyclotron current drive has been demonstrated. NTM suppression is a recent innovation that has enabled operation at higher β in existing experiments. Gyrotron sources are improving, but a *1 MW*, steady-state source is not yet available.

Lower hybrid sources *(~ 8 GHz*) are the most efficient current drive tool, but good coupling calls for a finite plasma density in the scrape-off-layer next to the antenna. In practice this would require measurements of low-power coupling on a BPX as input data for the design of a high power lower hybrid system on the same machine. A lower hybrid system is thus appropriate as an upgrade capability that would constitute a potential source of localized, off-axis current drive for FIRE and IGNITOR in order to suppress neoclassical tearing modes and perhaps extend pulse lifetimes somewhat before heating of the toroidal field coils becomes untenable.

Fueling by pellets launched from the outside of all three BPX candidates is possible, but penetration into the plasma core is more problematic at high densities and temperatures. A key innovation for tokamaks occurred in the 1990's with the introduction of inside pellet fuelling, which achieved superior fuelling efficiency and penetration as compared outside pellet and gas puff fuelling. The physics basis rests on particle drifts in a toroidal geometry. It is a challenge to BPX designers to incorporate inside pellet launch into their scenarios. Inside pellet launch could be possible on ITER-FEAT by locating the injector in the central solenoid core. Trajectories for FIRE and IGNITOR may also be possible but further design is necessary.

One should note that the radio-frequency techniques listed above rest on a highly developed, scientific foundation of wave propagation, absorption, mode conversion, and nonlinear wave-plasma physics. Although most of the applications have been to tokamaks, the theoretical foundations of wave-plasma interactions are generic and these radio-frequency capabilities are essential to the planned future stellarators and spherical tori.

The ultimate choice of heating method to be used in a burning plasma experiment depends strongly on the size of the device, the density of the plasma, and the strength of the magnetic field. In terms of performance the main heating requirement in a burning plasma experiment is that sufficient auxiliary power be available so that in conjunction with the alpha particle heating and ohmic heating, the plasma achieves a temperature of $T \approx 15\ KeV$ at the desired density. Past experimental experience has shown that the amount of heating power typically required is not too large so as to have a major impact on the overall power balance and recirculating power fraction in the reactor regime.

The issue of current drive is more difficult. As with heating there are a number of options. However, the efficiency of current drive is relatively low compared to that of heating. A substantial amount of power is required to drive a small amount of current. In fact, driving the total toroidal current by external current drive would require such large power levels that extrapolation to the reactor regime would be problematical for a steady state system. The steady state tokamak concept thus relies heavily on a large fraction of the total current being supplied by the bootstrap effect. That is, when properly aligned, the bootstrap current contributes a fraction f_B of the total current. The current drive system then only has to compensate for the difference once the volt-seconds of the transformer are consumed. For standard operation one expects $f_B \approx 0.3$, while for full advanced operation $f_B \approx 0.8$. The current drive system must then be capable of driving the fraction $(1 - f_B)$ of the total current in these operating regimes.

A slightly subtle point is that in principle it should not be very difficult to drive 100% bootstrap current. One simply turns off the ohmic transformer and continues thermonuclear and auxiliary heating until the plasma settles into a self-consistent magnetic and thermal equilibrium. Only a small amount of auxiliary power current drive is required near the magnetic axis where all four heating techniques have a documented ability to drive current. The difficulty is that the 100% bootstrap profiles do not in general have the high MHD β limits desired in a reactor. Thus there will be a tradeoff between achieving high β stable profiles while using the minimum on axis current drive possible. This trade-off cannot be well explored in existing experiments because resistive heating of the toroidal field coils limits the discharge duration to be comparable to (or less than) the current profile relaxation time. Finally, it is worth emphasizing that in the context of a BPX the current drive capability is only an issue in long pulse experiments in which τ_{pulse} exceeds the ohmic transformer flattop portion of the pulse.

Thus, for heating and current drive the critical performance parameters for a burning plasma experiment are the plasma temperature T and the net value of plasma current that needs to be driven: $(1 - f_B)I$.

C. Transport

A hot plasma is continually losing energy through a combination of heat conduction and radiation. If the operating point is to be sustained, these losses must be balanced through a combination of external heating systems and fusion-generated α-particles. In the burning plasma regime α-heating dominates external heating and conduction losses dominate radiation losses. An economically attractive BPX, therefore, requires a minimization of the conduction losses.

The Lawson Condition. A metric for conduction losses in the context of burning plasmas is obtained by considering a *0-D* model in which the thermal conduction losses are modeled by

$$P_{con} = (3/2)\, pV/\tau_E$$

where p is the thermal plasma pressure, V is the plasma volume, and τ_E is the energy confinement time. The remaining terms in the *0-D* power balance are fusion heating due to alphas, heating by external systems (which, for simplicity, is assumed proportional to the fusion heating consistent with a constant α-heating fraction, f_α: $P_{ext} \equiv [(1 - f_\alpha) / f_\alpha]\, P_\alpha$), and radiation losses from free-free bremsstrahlung. The helium ash (that is, fusion α-particles which have slowed down to reach thermal equilibrium with the plasma) concentration is obtained by balancing its generation through fusion reactions with its particle loss rate n_H/τ_H. These equations are solved for the confinement product, $p\tau_E$, required for steady-state power balance as a function of the plasma temperature, T.

The confinement product, $p\tau_E$, is displayed in Fig. 3 as a function of the plasma temperature for various values of f_α and τ_H/τ_E. The ignition threshold, where the alpha heating power balances all losses, is shown by the heavy black curve for $\tau_H/\tau_E = 1.0$. This *0-D* model demonstrates that entrance to the burning plasma regime is facilitated by operation with $10\ keV \le T \le 20\ keV$. In this temperature range a confinement product $p\tau_E > 6$ *atm-sec* is required to exceed $f_\alpha = 0.5$, while a confinement product of $p\tau_E > 11$ *atm-sec* is required for ignition.

More realistic models, which take into account radial profiles of temperature and density, find that the required confinement product decreases for peaked pressure profiles. However, impurities increase the required confinement product. As a result, the practical range of confinement products required for an ignition experiment can vary in the range $(p\tau_E)_{IG} \approx 5 - 20$ *atm-sec*, where p now refers to the volume averaged thermal pressure.

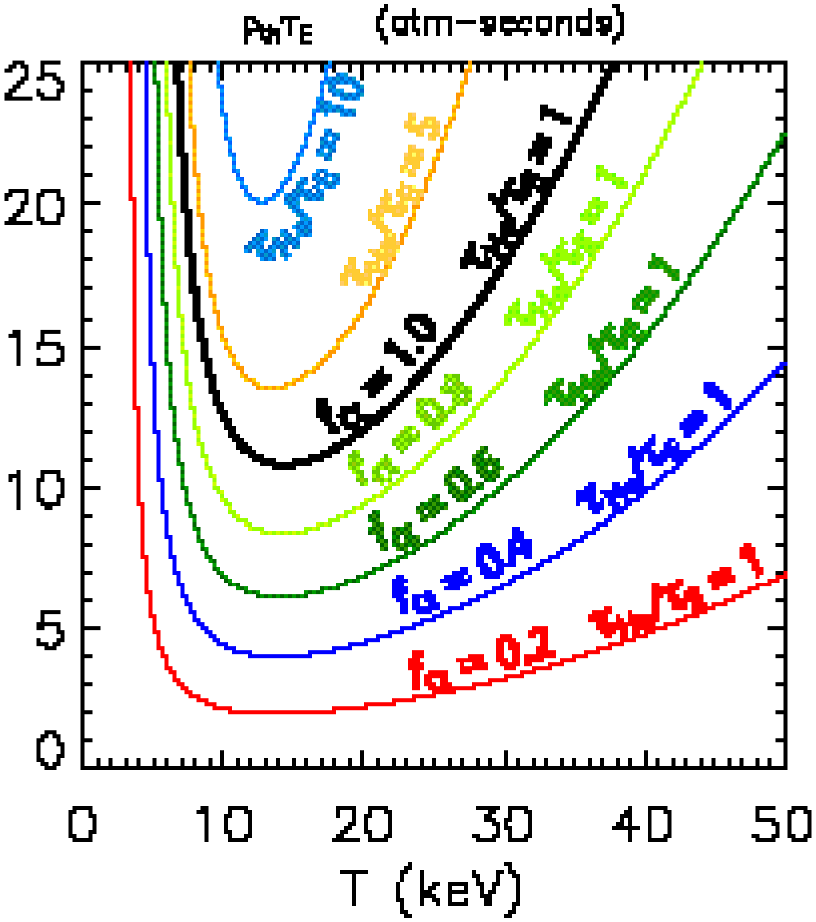

Figure 3 Confinement product required for fusion power balance vs. T. Ignition ($f_\alpha = 1$) at $\tau_H/\tau_E = 1$ is shown by the black curve. Subignited operation with $\tau_H/\tau_E = 1$ is depicted by the red, blue, green, and chartreuse curves labeled with the appropriate value of f_α. The gold and light blue curves depict ignited operaton with weaker helium pumping. All curves include trace amounts of Be (1%) and Mo (0.01%) for $Z_{eff} = 1.4$.

0-D Confinement Scaling Relations. Substantial effort has gone into extracting scaling relations for the energy confinement time from the experimental database. Such efforts typically find something like

$$\tau_E \propto I\, R^{3/2}/P_{con}{}^{1/2}$$

where I is the plasma current. Note that power balance implies that the thermal conduction power loss $P_{con} = P_\alpha + P_{ext} - P_{rad}$: P_{con} is the total heating power minus the radiation power. Inserting this into the 0-D power balance model, we find

$$p\,\tau_E \propto I^2 R^3/V \propto I^2\,(R/a)^2$$

with no explicit dependence on either the net heating power or the absolute size of the device![1]

This explains a major difference between existing tokamaks and a proposed burning plasma experiment - the plasma current. The largest existing tokamaks typically operate with I between 2 and $4\ MA$, while the proposed burning plasma experiments would all operate with plasma currents in excess of $7.5\ MA$. This increase in the plasma current is a major cost driver for burning plasma experiments. Any increase in the plasma current is subject to the limitation introduced in §III.A that $q^* = 5\ a^2 B\kappa/R\ I > 1.5$, or

$$I < 3.3\ \kappa\,(a/R)Ba$$

Thus, at fixed q^* the Lawson parameter scales as

$$p\,\tau_E \propto \kappa^2 B^2 a^2$$

Hence, increasing the plasma current requires an increase in the magnetic field, B, in the size of the device, a, in the plasma shaping (that is, an increase in κ), or some combination of the above. There are practical limits on plasma shaping ($\kappa < 2$), which have largely been reached in existing tokamaks. Hence, the design of burning plasma experiments is focused on the trade off between increases in size and magnetic field relative to existing tokamaks. Such increases in size and/or magnetic field have proved to be major drivers to the cost of such facilities.

Note that at fixed a/R and κ (which have similar values for each of the proposed BPXs) there are two qualitatively different strategies that one could use to achieve the necessary Ba product, involving different trade-offs between magnetic field and size. The first is to use high field copper magnets and relatively small size (IGNITOR and FIRE). This is the most economical approach to a BPX but the resulting devices are inherently pulsed. Non-ohmic current drive can somewhat increase the ratio of τ_{pulse}/τ_{CR} but ultimately the temperature rise due to ohmic heating in the toroidal field coils limits the pulse length, preventing steady state operation. The other strategy is to utilize lower field superconducting magnets and larger size (ITER-FEAT). Such devices are more costly. However, while initially pulsed, they can be upgraded to achieve much longer pulse lengths or even steady state operation

It is also possible to increase τ_E by operating in enhanced confinement regimes. Early tokamak experiments led to an empirical confinement relation for τ_E known as "L-mode scaling," the "L" denoting low confinement. It was later discovered experimentally that the addition of a sufficient quantity of external heating would cause the confinement time to suddenly jump appreciably. Once in this regime, τ_E scaled similarly as for L-mode except with a larger multiplying coefficient denoted by the symbol "H" for high confinement. This is known as the H-mode regime. The H-mode is now routinely realized in experiments and forms the basis for the performance projections for two of the proposed burning plasma experiments. Further

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[1] A more exact analysis, based on the dimensionally correct ITER IPB98(y,1) confinement scaling yields $p\,\tau_E \sim H_H^2 (I)^{2.70} (R/a)^{2.62} (B/P_{con})^{0.3} (n/n_G)^{0.88} k^{0.44} R^{0.66}$, where n_G was introduced in §III.A. The strong dependence on aspect ratio, R/a, (in addition to the plasma current) is ubiquitous, and tends to counteract the decrease in I with R/a at fixed q^*.

enhancements in energy confinement have been observed intermittently in experiments. The H-mode seems easiest to achieve in plasmas with divertors. In plasmas without a divertor, improved confinement is more likely to be achieved by peaking of the density profile. Pellet injection of fuel into the core has shown to lead to such density peaking. The physics description and technology of pellet injection is now in a development phase, and its successful development may be extremely significant towards reaching burning plasma regimes.

Transport Theory and Experiment. The importance of plasma transport to the design of a burning plasma experiment motivates careful study of the underlying physical mechanisms. The plasma temperature and density equilibrate within a magnetic surface on the ion transit time scale (that is, a few μs). Hence, the issue is the transport of particles, energy, and momentum across magnetic surfaces. Both theoretical analysis and the experimental database support the conclusion that there is an irreducible minimum transport rate set by neoclassical theory. Neoclassical transport results from the combination of binary Coulomb collisions and the finite radial width of particle orbits in the confining magnetic field in a toroidal geometry. Neoclassical transport correctly describes the rate of diffusion of poloidal flux across surfaces of toroidal flux (that is, the evolution of the plasma current profile); and it produces the remarkable bootstrap current wherein density and temperature gradients across magnetic surfaces generate a current flowing parallel to the magnetic field. While neoclassical theory governs ion energy transport in some experiments, the usual experience is that transport losses in both the electron and ion channels are governed by collective effects—plasma micro turbulence—which result in transport of particles, momentum, and energy that are very much larger than the predictions of neoclassical theory.

Plasma micro turbulence and the associated *anomalous* plasma transport have been the subjects of study by the magnetic fusion program throughout its existence. Improvements in the measurement of plasma equilibrium conditions, and of fluctuations in the plasma density and temperature, together with theoretical advances and the application of *3-D* direct numerical simulation have led to substantial advances in our understanding of plasma micro turbulence over the past decade.

Plasma micro turbulence results from linear instabilities driven by temperature and density gradients. Theoretical analysis predicts - and both experiment and direct numerical simulation confirm - that gradients in the angular rotation rate generally act to suppress these micro instabilities. Saturation of micro instabilities is expected to occur when the temperature gradient perturbation due to the microturbulence becomes comparable to the background temperature gradient. Numerical simulation of plasma micro turbulence to date has mainly focused on ion thermal transport. These studies indicate that ion thermal transport increases rapidly when the gradients in ion temperature are increased beyond critical values related to the linear instability thresholds, and empirical rules for the suppression of plasma microturublence by flow shear have been developed from such simulations.

Experimentally the situation is as follows. Observations confirm the existence of small-scale density fluctuations, on the order of an ion gyroradius (i.e. ~ *1 cm)* in all tokamak discharges. Also, this microturbulence typically has a short correlation time (i.e. ~ 100's of μsec). The experimentally observed ion temperature gradients are somewhat in excess of the predicted thresholds (as expected from the theoretical picture) and the fluctuation level is in accord with theoretical estimates.

Thus the conceptual framework of a scale separation between the turbulent micro-fluctuations and the plasma scale size is supported by theoretical analysis and by experimental observation, thereby justifying a transport approach to heat loss, but one in which the diffusion coefficients are generally functions of cross-field gradients. One can conclude that the theoretical picture of anomalous heat transport is in semi-quantitative agreement with observations and provides the correct conceptual basis for projecting energy confinement in BPX plasmas. Yet, in spite of this impressive work, important uncertainties remain in determining the heat loss from BPX plasmas. In large measure, these arise from the requirement for quantitative projections of turbulent transport process to better than a factor-of-2 in the confinement figure-of-merit $p\tau_E$, which must increase by a factor-of-20 over present experiments. Moreover, the anomalous heat diffusivity can change with the non-dimensional elongation κ, the safety-factor q^*, the inverse aspect ratio a/R, and rotational shear as well as with local temperature and density gradients. Numerical simulations have barely begun to explore this large parameter space while, upgraded gyrokinetic codes - which include a more realistic electron model, magnetic fluctuations - are just now entering the testing phase. These upgraded codes should allow us to study electron thermal transport and particle transport, which are not present in the existing models, which utilize a simple fluid model for electrons.

Transport Barrier Formation. Tokamak plasmas are observed to support axisymmetric flows within magnetic surfaces at velocities up to 100's of km/s. Radial variations in this flow velocity ("flow-shear") are found to suppress ITG turbulence and the associated anomalous transport, leading to the formation of transport barriers. Enhanced confinement modes are often associated with the appearance of transport barriers. For example, the H-Mode is associated with the formation of a transport barrier at plasma edge, while core transport barriers have also been observed in experiments. This line of research supports the 'Advanced Tokamak' program - an effort to achieve substantial improvements in tokamak performance through simultaneous control of the profiles of pressure, density, flow, and current.

Electron Transport. Anomalous electron transport is ubiquitous in the plasma core. It is less well studied both experimentally and theoretically - largely because the most reliable plasma heating system, neutral beams, primarily deposits power in the ion channel, and the theoretical effort has concentrated on understanding the experimental data. However, anomalous electron transport will surely be important in a burning plasma experiment because fusion generated α-particles mainly heat electrons in a D-T burn. In the burning plasma regime the collisional temperature equilibration time is small compared to the energy confinement time (this is in contrast to many current experiments where the opposite is true). As a result, heat will be efficiently transferred from the electrons to the ions via collisions and we may expect $T_e \approx T_i$. With (nearly) equal temperatures the electron and ion channels are both important to the energy confinement. While ion-driven instabilities - like the ITG mode - produce both anomalous ion and electron transport, there are other instabilities, which produce anomalous electron transport in the absence of anomalous ion transport. These electron-driven instabilities have shorter wavelengths and higher frequencies than is characteristic of ITG turbulence. Plasma flow shear will likely be ineffective in suppressing such short wavelength electron-driven instabilities. The available experimental evidence shows that anomalous electron heat transport proceeds at rates similar to anomalous ion heat transport. Hence, we do not expect anomalous electron transport to result in dramatic changes in the energy confinement time.

Transport Modeling. The available computational resources limit full 3-D direct numerical simulation of plasma turbulence to time intervals of a few milliseconds. While this is adequate to the study of plasma micro turbulence, it is very much less than either the energy confinement time (which ranges from 0.1 to 1 second in existing high-performance tokamaks) or the duration of typical plasma discharges (which can range up to 10's of seconds in current devices). Hence, reduced 1-D models have been developed to describe the effect of the plasma turbulence on the profiles of temperature and density. These models use transport coefficients motivated by simulations of plasma turbulence or other theoretical considerations. 1-D transport models have been compared to the existing experimental database with reasonable success. However, our collection of reduced transport models have two serious limitations in projecting the performance of a proposed burning plasma experiment: (1) They require the values of the plasma density and temperatures at the top of the edge pedestal as a boundary condition (see the discussion of plasma edge transport below), and (2) they can give significantly different quantitative results when projecting the performance of particular burning plasma experiments because of the relatively large extrapolations involved. In essence, the nonlinear micro turbulence problem is so complex that our first principles understanding of transport is still not sufficiently reliable to displace experimentally based empirical scaling relations.

Plasma Edge Transport. Plasma edge turbulence differs from plasma core turbulence in that there is no separation between equilibrium scale lengths and the characteristic wavelength of the plasma fluctuations - a circumstance which simultaneously complicates analytic studies (due to the loss of a small parameter) and eases direct numerical simulation (by reducing the required dynamic range in spatial scales). The best plasma performance - the high-performance H-mode - is associated with the suppression of anomalous transport in the edge by plasma flow shear, and often the recurrence of a new instability - the edge-localized mode, or ELM (see §III.A and III.D). ELMs are important to the transport problem because stability against such modes sets an upper limit to the pressure gradient at the plasma edge. This edge pressure gradient, together with an estimate of the width of the edge pedestal would provide the boundary condition needed by the 1-D models of core plasma transport. Uncertainty in the edge pedestal height contributes at least as much to our uncertainty in projecting the performance of a specific burning plasma experiment as the uncertainty in our 1-D core transport models.

Summary. The above discussion provides one of the primary motivations for building a burning plasma experiment - to learn about transport in the alpha dominated regime. Empirical scaling relations are very useful for designing new devices but their lack of first principles understanding is a cause for concern. The reason is that relatively small changes in these relations applied to a large extrapolation in f_α from present values (on the order of a factor of 10 in Q), lead to small but nonetheless, finite differences in the predicted f_α (on the order of a factor of 2 in Q) in a BPX. On the other hand while substantial progress has been made, and continues to be made on first principles theoretical/computational modeling of plasma micro turbulence and the resulting anomalous transport, these studies still have a long way to go before being quantitative enough to provide a reliable design tool. The problems are enormously complex and the existing state of the art computing capabilities are still not up to the task. The conclusion is that we know and understand enough to build a BPX that will produce large amounts of alpha heating although we cannot predict, with for instance the same accuracy as for MHD instabilities, what the resulting f_α value will be. We should design for $f_\alpha \geq 2/3$ using the best empirical scaling available but cannot guarantee that this value of f_α will be achieved. Learning about transport scaling is one of the primary scientific challenges in a BPX and what we learn will have a large impact on the future desirability of a fusion reactor based on tokamak physics.

Finally, in terms of confinement performance in a burning plasma experiment, the critical measures are the achievable values of $p_{th}\tau_E$, H, and f_α.

D. Plasma-Boundary Interactions

The interaction of the plasma edge with the wall presents several difficult challenges for a burning plasma experiment based on the tokamak or for that matter any magnetic configuration. The totality of these effects are generally generic to toroidal plasmas, although details will differ due to the different physics and geometries. There are two basic issues: (1) power and particle handling by the first wall including helium ash removal and (2) determination of edge temperatures and densities and their impact on core transport. The relevant power and particle handling issues have been known for some time and studied in some detail but have not been a dominant problem in existing experiments. The reason is that pulse lengths have been relatively short and wall loadings have been relatively low. This situation will change dramatically in a burning plasma experiment where the first wall will be bombarded over long pulse lengths by hot, high density core plasma particles being lost from the system and from fusion produced neutrons. The strong impact of edge temperature and density on core transport has been recognized in recent years. Thus, the problem has received considerable attention. However, it is a complex problem involving atomic, molecular and materials sciences as well as plasma physics. Below is a description of the edge physics issues in non-burning plasmas and their potential impact on a burning plasma experiment.

The tokamak edge consists of the thin volume just outside the separatrix, where the magnetic field lines are “open,” thereby making direct contact with material walls. Since the edge is strongly coupled to the closed field line region just inside the separatrix, this thin inner volume is also usually included in analysis of edge physics. The goal is to acquire a unified description of edge physics including the important issues of plasma-wall interactions and the formation of edge “temperature pedestals.” Such pedestals, which were first discovered experimentally, represent barriers to transport and lead to enhanced confinement in the plasma core. (This regime is known as “H-mode” confinement with H denoting “high.”)

As a general comment note that the dominant physics is very different on open and closed field lines. Thermal conductivity parallel to a magnetic field is extremely large, yielding nearly constant pressure and often constant temperature on closed magnetic flux surfaces. On such surfaces transport losses result from the much slower cross-field processes. In contrast on the open field lines outside the separatrix, the plasma forms a narrow “scrape-off layer.” The layer is narrow since parallel transport losses to the divertor are rapid relative to cross-field transport. The physics of parallel transport consequently plays a major role in how the plasma is finally lost and how it finally deposits its energy on the wall. In addition, helium ash, which consists of the residual α particles after they have transferred their energy to the plasma core, also flows along the open field lines. The ash must be pumped from the vacuum vessel in order to prevent buildup in the confined plasma, an undesirable situation that would dilute the density of the fusion producing deuterium-tritium fuel.

The energy loss to the walls in a burning plasma will average $1\ MW/m^2$ although local values may be much higher. There are three primary paths of energy loss: (1) At low edge densities the plasma extends along field lines which impinge upon the first wall, typically the divertor plate. The divertor plate thus acts as a direct absorber of energy, plasma particles, and momentum. Because the scrape-off layer is narrow, the energy density can be locally so high as to melt or otherwise damage the surface. Care must obviously be taken to avoid this situation. (2) At high edge densities the plasma may literally "detach" itself from the divertor plate. Between the plasma and the plate is a substantial size transition region in which the plasma recombines into neutrals. Energy loss now occurs by radiation rather than by plate bombardment and is thus spread over a much broader area. The result is a significantly reduced likelihood of damage. (3) Finally, impurities can be deliberately injected into the toroidal plasma, thereby forming a highly radiating layer in the vicinity of the separatrix. Most of the plasma energy loss is again spread over the walls of the confinement vessel, reducing the energy density below damage thresholds. This leads to the so-called radiating impurity (RI) mode, used recently with success on JET and other experiments.

It should be noted that the IGNITOR experiment does not have a divertor. The plasma edge makes direct contact with a large fraction of the first wall as opposed to the small area of a divertor plate. This reduces the peak heat load problem but raises the possibility of substantial amounts of wall impurities and of recycling fuel uncontrollably penetrating into the plasma. It is precisely to avoid these problems that the divertor is used on most tokamak experiments. However, the IGNITOR strategy of operating at much higher densities than most tokamaks allows it to tolerate a larger absolute amount of impurities because the fractional content still remains small, as seen in high density experiments in the Alcator series of experiments and in FTU. One design guideline for IGNITOR is that it must have sufficient diagnostics and feedback control to prevent the plasma from leaning only on a local portion of the wall, as this would concentrate the heat over a small area.

If IGNITOR operates in the radiating impurity (RI) mode, it is likely that a pumped limiter will be required to control the impurity level in the plasma edge. This limiter will also pump the helium ash. The operating space for fusion burn in the RI mode has been explored in pumped limiter experiments in TEXTOR. Modeling finds that the fraction of fusion power radiated is a sensitive function of several parameters including: (a) the helium lifetime (normalized to τ_E), (b) impurity particle lifetime (normalized to τ_E), and (c) fuel dilution by the helium, the radiating impurity, and any other impurities. The operating space increases at high density, but detailed experiments and modeling will be needed to determine if an appropriate solution exists for IGNITOR. If so, a development program will likely be required for this limiter.

As stated, the issues just described are present but not dominant in existing plasmas. However, in the burning plasma regime these problems become far more important. In addition new effects arise that will impact the edge plasma. At the most general level, the fusion power in any likely device will be sufficiently high that operation at low edge density, which may be desirable for good core confinement, may not be possible. A higher density might be needed to operate in a mode in which substantial power is radiated in the scrapeoff layer below the X-point and in the divertor, thus avoiding edge power density limits on the divertor plate. This is of particular importance to advanced tokamak operation because of its requirements for current profile control. Further "inventions" will be needed in order to handle the plasma energy without badly damaging surfaces; the most straightforward approach is to use highly tilted divertor plates but this increases the vessel size and cost significantly. Overall, our current state of knowledge in this area is not as advanced as in other areas. It would appear that windows of acceptable operation are possible, but these windows are not very wide at present. The conclusion is that development of an interesting advanced tokamak will require a better physics understanding of the critical phenomena, and some new ideas to adequately handle the exhaust power.

Separate density control of the edge and core will provide a flexibility that may be essential in a burning plasma. The core can be fueled, for example, by injecting pellets from the high magnetic-field side, allowing optimization of the core density. Additional edge fueling is required to meet divertor requirements. Pumping in the divertor will provide additional control over the edge density but must be consistent with handling the helium ash.

If a radiating divertor is used another problem arises. High impurity radiation, which is favorable for reducing heat loads, also leads to core fuel dilution and cooling, a situation that is clearly undesirable. It may also degrade the pedestal temperature and thus the core confinement. The requirements on a radiating or detached boundary (or other means of spreading the power) must be consistent with the core requirements, e.g., for a certain power density. A burning plasma experiment will be needed to demonstrate that the conditions can be met simultaneously.

Pumping of the helium ash is sensitive to the operating regime and will need further scientific investigation although it is presently expected not to be a critical issue because the length of the burn phase of the pulse will not greatly exceed the helium build-up time. Both pumping and radiative control are being evaluated in existing experiments, although final resolution will require a burning plasma.

Energy confinement on the closed field lines in the H-mode is sufficiently long that edge pressure gradients often grow continuously until MHD disturbances, known as edge localized modes (ELMs), cause them to suddenly collapse. As a result, in long-pulse H-mode tokamak operation, bursts of energy and particles are injected into the scrape-off layer by ELMs. The particular MHD instability involved in the ELM is an ideal mode (i.e. plasma resistivity is not important) known as the "ballooning mode" which tends to localize around regions of high pressure gradient and unfavorable magnetic field line curvature.

Just before the ELM crash, a very steep edge temperature gradient develops over a distance of a few centimeters. The temperature in the edge pedestal rises to 1-2 keV or more and the system crosses the critical pressure gradient corresponding to the ballooning mode stability limit. Often the detailed structure of the resulting instability appears more complicated than one would expect from ballooning modes alone, and may involve a trigger by a precursor instability. In any event, the resulting particle and energy releases are large and rapid, and scaling to the burning plasma regime predicts physical damage to the divertor hardware. Consequently, H-mode operation in the presence of ELMs should be avoided in a BPX.

A second type of ELM exists that is thought to be driven by resistive MHD instabilities with magnetic reconnection playing a key role in the resulting energy and particle losses. Resistive ELMs occur at a lower pedestal pressure than ideal ELMs. They release energy and particles at a rate that is expected to be experimentally acceptable, typically a factor of 5-10 less than for ideal ELMs. However, since the resistive ELM is excited with a lower pedestal temperature, this unfortunately results in a lower energy confinement time for the core plasma. A good strategy to combine the high core confinement associated with steep gradient ideal ELMs and the limited energy release associated with resistive ELMs is to operate at relatively high pedestal density ($\sim 10^{20} m^{-3}$). In this regime the instability boundary for resistive ELMs approaches the ideal ballooning boundary. Near this overlap, confinement is not degraded as significantly by resistive ELMs, and the energy release is expected to be acceptable; this region is proposed for ITER-FEAT H-mode operation.

It is thus clear that fundamental MHD processes related to the steep transition from closed to open field lines will constrain the operating space of a diverted burning plasma in H-mode. The basic physics may be broader than in tokamak operation, as similar processes could occur in any well confined toroidal plasma with a divertor due to the inevitably large energy losses along open field lines to material walls.

A quantitative issue that has a crucial role on the behavior of the edge and its impact on the core is the width of the scrape-off layer of plasma on open field lines leading to divertor or limiter surfaces. The difficulty is that the gradient lengths (across the magnetic field) of temperature and density are determined by turbulent transport from instabilities that are only now beginning to be understood; additional experiments in existing machines are required to understand this physics. If energetic alpha particles are not well confined and thus have a moderate or large density in the vicinity of the separatrix, the physics of these instabilities may be affected. This could result in enhanced radial energy transport and thus broaden the edge width; it could also affect the auxiliary power threshold for the high confinement H-mode transition.

Finally, the materials used in the divertor have issues that are neither fully understood nor resolved. The choice of materials may affect retention of tritium in walls away from the divertor strike area where plasma bombardment does not cause re-emission. Carbon is thought not useable for this reason, but there is little data on other materials. Resolution of this issue will require a burning plasma experiment although some measurements can be made on existing experiments. Other issues such as erosion and dust generation need to be addressed in a burning plasma or in other long-pulse experiments. Finally, the coupling of plasma bombardment effects with *14 MeV* radiation damage will be difficult to evaluate until a burning plasma is studied. Such effects will be important in most magnetic confinement concepts, and to some extent in inertial confinement concepts.

E. Alpha Particle Physics

Probably the most exciting new science issues in a burning plasma involve phenomena that arise solely because of the presence of α particles. A number of such phenomena have been predicted by theory. However, they either do not exist in current experiments or else exist in a much weaker form. The phenomena of interest involve the impact of alpha heating on shaping the equilibrium profiles and determining the plasma performance, the overall thermal stability of a burning plasma, as well as the possible presence of new classes of MHD-like instabilities driven by the α particles. In addition the presence of α particles can have a strong and direct effect, sometimes positive and sometimes negative, on certain macroscopic MHD modes. It is crucial that these phenomena be investigated, understood, and ultimately controlled for fusion science to progress.

In the burning plasma regime, the alpha heating determines equilibrium profiles that affect the energy transport and the MHD stability, which in turn determines the intensity of the alpha heating. Such a synergistic interaction is probably the single most important overriding effect that needs to be investigated in a burning plasma experiment. Here we focus our attention on the specific consequences that follow from the presence of a large fusion power and population of alpha particles and which contribute to the synergistic effects.

The first phenomenon of interest involves control of the fusion burn, the issue of thermal stability. As the number of fusion reactions increase, the temperature rises until the plasma reaches the desired operating point in the burning plasma regime, perhaps finally even igniting. At the operating point the system is in equilibrium with heat conduction losses balanced by the combination of external and α powers at the desired operating temperature. A potential difficulty that can arise is that the equilibrium point may be thermally unstable, with α power increasing more rapidly with T than conduction losses. When this occurs the temperature can runaway and some form of feedback burn control is needed. However, a substantial operating regime of scientific interest exists where this problem does not arise; that is, thermal losses increase more rapidly with T than α power. Gaining access to this stable regime of burning plasma physics requires a careful time evolution in n, T, P_{ext} space with adequate controls of the density and external auxiliary power. Learning how to control the time evolution of the plasma to achieve this goal is a major challenge for a burning plasma experiment. In addition to the n, and P_{ext} controls, one requires sufficient alpha power corresponding to $f_\alpha > 2/3$ to investigate the issue of thermal stability.

The second phenomenon of interest involves new classes of instabilities directly driven by the alpha particles. Such instabilities have been observed to cause loss of energetic particles in energetic particle injection experiments and in a weakened form in existing D-T experiments. In general even virulent alpha particle driven instabilities do not lead to macroscopic destruction of the plasma as in a disruption. This result is expected to hold in the burning plasma regime as well. Nonetheless, in regimes of strong alpha particle instability excitation, these modes may be detrimental to performance in the sense that they may lead to an anomalous loss of α particles. If these losses occur on a time scale fast compared to the time in which the α particles give up their energy to the bulk plasma then the equilibrium plasma power balance is degraded. There is a net reduction in the α power delivered to the plasma to balance the background plasma heat losses. This leads to a lower temperature and perhaps even to a loss of access to the dominant burning plasma regime.

The primary α particle driven instability is that due to an Alfvenic mode, the Toroidal Alfven Eigenmode (TAE). This mode is excited because of the presence of an alpha particle pressure gradient and the fact that α particle velocities are comparable to the Alfven speed which allows for a destabilizing particle-wave resonant interaction. The background plasma by itself supplies mechanisms by which TAE modes damp in absence of energetic alpha particles (e.g, one such mechanism is a collisionless form of damping known as "ion Landau damping") and these mechanisms counteract the destablizing alpha particle effect. Whether or not these modes are excited depends upon the parameters of the specific experiment under consideration. There is great scientific and practical interest in understanding the behavior of TAE instabilities in a burning plasma. This is only partially possible in existing experiments. In general it is difficult to reliably extrapolate the different regimes of drive and damping that are accessible in present day experiments, to that which will exist in a plasma dominated by alpha particle heating. In addition a burning plasma experiment, characterized by a plasma current significantly larger than in present day experiments allows the TAE modes, if unstable, to have a broader wave length spectrum. The breath of the spectrum induces different wave saturation properties than in present day machines and as a result different criteria for the onset of global alpha particle diffusion.

A critical parameter in the investigation of the excitation of TAE modes is the ratio of the Alfven velocity divided by the alpha particle velocity, which should be less than unity for the strongest interaction. This condition is invariably satisfied in a burning plasma experiment. In addition, the alpha particle drive is proportional to $r\nabla\beta_\alpha$ (where r is the minor radius and β_α is the ratio of alpha particle pressure to magnetic pressure) as well as other more complicated relations that depend on the magnetic geometry. Detailed calculations of TAE stability show that under nominal operating conditions IGNITOR will be stabilized by background ion Landau damping. Numerical studies for the original ITER design showed that the TAE mode was barely stable for its nominal design parameters. It appeared that regimes where the TAE mode is unstable could be accessed. There is one damping mechanism, the so-called radiation damping (due to the mode conversion of a TAE mode to a radiating Alfven-like mode) that is sensitive to the shape and other characteristics of the magnetic flux surfaces of a tokamak. For circular shaped flux surfaces, this mechanism has a strong stabilizing property on the TAE mode (often stronger than ion Landau damping). In a shaped tokamak it is expected that this stabilizing mechanism will be reduced but the proper and rather sophisticated numerical calculations, which are needed to study this effect, have not yet been performed. At present detailed stability calculations of the TAE modes are still needed for FIRE and ITER-FEAT.

For a conservative approach to the burning plasma regime, it is required that $r\nabla\beta_\alpha$ be sufficiently small to provide stability against TAE modes. However, the flexibility of varying $r\nabla\beta_\alpha$ to test the TAE's stability boundaries and to study their effects on plasma performance is a highly desirable characteristic for a burning plasma experiment.

Next, consider the interesting situation in which α particles actually stabilize a certain class of weak MHD instabilities but in the long run may lead to a serious degradation in performance, perhaps even a disruption. The situation arises as follows. We note that there can be a relatively large partial pressure of alpha particles in the center of a burning plasma [i.e. between *10-20 kev* the following relatively simple formula applies: $\beta_\alpha/\beta \sim 0.3\ (T_k/20)^{5/2}$ where T_k is the plasma temperature in *keV* and we assume $T_i = T_e$]. However the high energy of the alpha particles compared to the background plasma is known to alter standard MHD behavior, frequently producing stabilizing effects. Many standard tokamaks operate in the presence of a weak internal MHD instability that periodically redistributes the central plasma energy to the mid-region of the plasma $r < a/2$. The instability produces a cyclic response (an internal MHD crash with a small reduction of the central temperature, followed by a thermal restoration to again trigger a new internal MHD crash and so on) which is known as the "sawtooth" oscillation. The net effect of the sawtooth instability may even be favorable as the benign relaxation prevents the center of the plasma from overheating. Now consider the effect of α particles. It has been shown experimentally and theoretically that high-energy α particles can stabilize the sawtooth oscillation if the α particle pressure gradient is sufficiently high in the center of the plasma. When this stabilization occurs, the central plasma may then continue to heat to higher temperatures, ultimately releasing its energy in a large burst known as a giant sawtooth. This release contains a much higher quantity of thermal energy than a normal sawtooth oscillation and might possibly induce a disruption. It will be necessary to determine how to control the internal plasma temperature to prevent the excitation of such giant sawtooth events.

Lastly, when a large population of alpha particles is present, as occurs when the plasma temperature exceeds *20 kev*, it is possible for the alpha particles to induce Alfvenic instabilities in regimes where discrete modes otherwise did not exist. These modes are known as Energetic Particle Modes and as their onset criteria are somewhat complicated to evaluate, detailed calculations still need to be performed. However, some preliminary calculations on the FIRE design has indicated the possibility of such an instability arising. Such modes need to be investigated further in regimes where the plasma temperature is relatively high.

The investigation of AT physics brings in another crucial role for the understanding of alpha particle behavior. It has been established that without alpha particles, there is improvement in plasma confinement and sustainment properties in AT regimes. However, it is essential to learn whether alpha particle physics will be compatible with AT operation. In AT operation of a given machine, the plasma current is generally lower than in standard operation. Thus, both external magnetic field ripple and internal magnetic field perturbations from Alfven or MHD instabilities may have a larger deleterious effect on alpha particle confinement in AT operation than in standard operation. Further, it is expected that the Alfven spectrum will be easier to excite, particularly in the region of reversed shear, characteristic of AT operation. Hence, alpha particle physics issues in the AT regime is likely to be an even more crucial link in the overall self-burn scenario, than in the standard plasma burn scenario.

The conclusion is that a burning plasma will likely exhibit a new range of phenomena driven directly by α particles. It is desirable that a burning plasma experiment exhibit some flexibility with respect to the magnitude of β_α. A low enough value of $r \nabla\beta_\alpha$ will prevent alpha particle driven instabilities from being excited and facilitate the access into the burning plasma regime.

On the other hand, a sufficiently large value of $r\,\nabla\beta_\alpha$ allows the study of the excitation and the consequences of such instabilities once the burning plasma regime has been accessed. It is important to investigate these phenomena, not only for their scientific interest, but because they can have an important impact on plasma performance. The fusion power produced increases as β^2 and the larger its value the more efficient the ultimate performance for energy production is likely to be. Further, one ultimate goal of AT operation is to achieve higher β values, which in turn implies higher values of β_α. It is essential to show that the added effect of fusion produced energetic alpha particles is compatible with AT operation.

F. Pulse Length

It is clear from the above discussion that for a burning plasma experiment to be successful it must achieve a high level of performance in the regime of strong alpha heating. Achieving the desired plasma parameters *(i.e.* β, β_α, τ_E, f_B, *etc.)* is a major physics goal of such an experiment. However, it is not the only physics goal. Since the ultimate aim of fusion research is to develop the knowledge base necessary to build a steady state fusion power demonstration plant, it would be desirable that a burning plasma experiment demonstrate that high performance can be achieved under near steady state operating conditions. High performance during transient operation may not be sufficiently convincing or well understood that one can reliably extrapolate into the reactor regime.

The three primary designs for a burning plasma experiment, FIRE, IGNITOR and ITER-FEAT, are all pulsed devices and to satisfy the above requirement implies that they each must be capable of a sufficiently long burn pulse length, denoted by τ_{pulse}. (Note that only ITER-FEAT may be upgradable to steady state operation because of it use of superconducting magnets.) Since pulse length is a direct driver of cost, the question naturally arises as to specifically how long a pulse is required.

The answer is not an absolute value in terms of seconds but is instead measured with respect to various natural physics time scales that are design dependent. Of the many time scales that arise in a burning plasma experiment there are three relatively long ones that are of interest. The first is the energy confinement time τ_E that measures the natural cooling down time of the plasma. Clearly, τ_{pulse} must be greater than τ_E in order to investigate energy transport and global burn control in a burning plasma. The three proposed burning plasma experiments satisfy this condition.

The second time scale of interest is the helium ash removal time τ_H. This is the time required to remove the alpha particles after they have given up their energy to the plasma. If they are not removed rapidly enough their population builds up in the core, diluting the fusion fuel. Avoiding this problem requires strong pumping in the divertor region. FIRE and ITER-FEAT have such a capability and their pulse lengths are sufficiently long to investigate this phenomenon. Even without pumping, however, the alpha buildup would not be so large during the anticipated pulse length during the first stage of operations as to dominate the core burn. IGNITOR does not have a divertor. However, the alpha buildup is not expected to be a serious problem and is thus not a primary area of investigation.

The third time scale of interest is the current profile redistribution time $\tau_{CR.}$ This is sometimes called the "skin time" of the plasma and is quite long because the resistance of the plasma *R* is very small at burning plasma temperatures *(15 KeV).* Typically this time is in the range of several to hundreds of seconds. To achieve essentially steady state behavior requires that the pulse length greatly exceed the equilibration time. This is a particularly important requirement for advanced tokamak operation in which the naturally equilibrated steady state profiles must still correspond to high performance plasmas with high values of β and f_B. In each of the proposed burning plasma experiments the pulse length resulting solely from the ohmic transformer is comparable to the equilibration time. True steady state operation, however, requires greater pulse lengths that are generated by auxiliary current drive in the absence of the ohmic transformer. In practical experimental terms this translates into the availability of current drive sources included in the design and the possibility of extending the magnet pulse length, which is easier with superconducting magnets. ITER-FEAT addresses this issue at a reasonable level and is capable of fully addressing the issue with future experimental upgrades. Because of their high-density plasma, advances in current drive technology are required to drive large currents in FIRE and especially IGNITOR. Eventually, if developed, a current drive system could be used in both FIRE and IGNITOR to address some long pulse physics issues, keeping in mind, however, that ohmic heating in the toroidal field coils will always set a limit on the maximum possible pulse length. The simultaneous achievement of high performance and external current driven long pulse operation substantially increases the cost of a burning plasma experiment. The fusion community must carefully examine the cost and physics trade-offs between high performance and long pulse operation in order to define an optimum burning plasma experiment.

In summary, the main requirement for long pulse external current driven steady state operation in low, medium, or high performance discharges is to have burning plasma pulse duration exceed the plasma current redistribution time: $\tau_{pulse} > \tau_{CR}$.

G. Generic Contributions of a Tokamak Burning Plasma Experiment

General Considerations:

A tokamak-based, burning plasma experiment will engage in both scientific exploration and demonstration. This Section addresses the question: To what extent will data from such an experiment prove useful in aiding and accelerating the development of other toroidal fusion energy configurations? There are issues at two levels. First, will information from a tokamak-based BPX be sufficiently generic to impact development of other fusion configurations in a cost-effective way. That is, what we learn should not be overly specific only to the tokamak. Second, while each of the three candidate BPX experiments will make a major contribution to burning plasma physics, how different and transferable will the knowledge gained be when comparing one device with another. This could have an impact on the final choice of BPX.

There are many issues in a tokamak that are of importance to other configurations and essentially all are addressed at some level in the proposed BP experiments. The difficult choices involve determining just how important each issue is, and just how much should one be willing to spend to add the corresponding experimental flexibility. Some examples of important issues that are generic to other concepts are as follows. Should the BPX have sufficient flexibility to explore the level of the bootstrap current that can be driven under varying conditions? Could a tokamak BPX investigate both optimization of a plasma with a small bootstrap current as well as demonstrate that a steady-state plasma can be maintained by a strong bootstrap current? Should the BPX explore the conditions under which alpha-driven modes are (a) stable, (b) unstable but benign, or (c) unstable and cause unacceptable losses? The three candidates discussed in this report will provide differing opportunities to explore various physics issues, and one of the charges to the proposed Snowmass meeting, as discussed in Sec VI, is to evaluate the cost-benefit trade-offs of each option. The community judgment on the importance of using the BPX to develop a broad understanding of these and other issues will determine the extent to which flexibility will be a major facility design goal.

As we examine the issue of applying the physics from a burning plasma to other concepts, we need to keep in mind that the radiation environment in such an experiment will make scientific exploration much more difficult than in a non-burning plasma. This is one of the reasons for maintaining a strong base program, including a tokamak component that can address issues that do not require either burning physics or the attaining of plasma parameters that cannot be obtained other than in a large, high power tokamak. It also suggests that initial operation of a BPX utilize non-fusing hydrogen plasma to explore those science and technology issues that do not need a burning plasma. An example is erosion of plasma facing material components.

The magnetic approach to controlled fusion energy has long supported a variety of specific configurations, such as the tokamak, stellarator, RFP, spheromak, and FRC, etc. at various resource levels. The key point to make first is the very high degree of commonality both in experimental techniques that are used to design, construct, diagnose, and interpret experiments and in the common theoretical concepts, approximations, models, and stability analysis that underlie our ability to extrapolate scientific results towards a fusion energy goal. Of course, each configuration is sufficiently different that it will often require its own specific codes for uniquely important physics. Thus, modern ideal and resistive MHD codes are applicable to all symmetric toroids, but fully understanding the effects of helicity and the magnetic dynamo generally requires additional modeling and codes. Tokamak codes are inadequate to treat the more difficult 3-D stellarator design issues. Nonetheless, the standards of experimental and theoretical research are common and have been largely set by tokamak research, which benefits from a high level of support. New standards of predictive capability and operational reliability will be required to support a tokamak burning plasma experiment, and the standards so set will apply to future proposed experiments. In this sense, it is important that the entire magnetic fusion community be involved in defining a burning plasma experiment.

Classes of Toroidal Magnetic Confinement Configurations:

Early in the magnetic fusion program, it was recognized that any magnetic confinement configuration that could confine an isotropic velocity distribution would have to be topologically a torus. Two principal species evolved: Class 1) Toruses with strong, externally imposed magnetic fields (such as the tokamak, spherical torus, and stellarator) and Class 2), configurations with magnetic fields generated by currents primarily within the plasma itself (such as spheromaks, RFPs, FRCs). The first class (“strong external field toroids”) is further split by mathematical necessity into two sub-classes. There are *2-D* axisymmetric "tokamak" configurations that require a current in the plasma to attain confinement, and *3-D* stellarator configurations that can confine plasmas by magnetic fields which are entirely externally imposed but are mathematically required to be 3-dimensional. For tokamaks and the spherical torus, axisymmetry implies conservation of canonical angular momentum and assures individual particle confinement. For stellarator configurations, a major breakthrough occurred in the 1980s, which established realizable quasi-symmetry principles that assured confinement of individual particle orbits. Interestingly in one realization of these principles, the quasi-axisymmetric stellarator, bootstrap currents play an important role as they do in the tokamak. In the second class of toroids ("weak external field toroids") the research emphasis has been on axisymmetric configurations, although three-dimensional, helical RFPs are, in principle, possible. This taxonomy of generic toroids continues to this day and it is the goal of this section to set forth examples regarding how one can utilize data from a tokamak burning plasma experiment to increase one's understanding of other toroids.

A common requirement of these different toroidal configurations is that they must each satisfy the MHD equilibrium equation $\boldsymbol{JxB = \nabla p}$ and possess both magnetic surfaces $\boldsymbol{B \cdot \nabla p = 0}$ and confined individual particle trajectories. A common energy principle is used to assess ideal MHD stability. Again, each generic toroid requires its own equilibrium and stability calculations but we find common methodology and standards, such as in equilibrium and stability codes that were pioneered by tokamaks, being brought to bear on other toroids. The science of stabilizing resistive wall modes is being developed in tokamaks and may be applied to a burning plasma to increase beta limits. This science is central to long-pulse operation of the spherical torus, spheromak and RFP, although the important mode spectra differ. In another example, as we develop a deeper understanding of the effects of alpha particles on MHD stability in a tokamak BPX, this understanding and many of the techniques developed will be directly applicable to other devices. There may also, of course, be additional physics important in these devices. One example might be coupling of the alpha particles to low frequency magnetic turbulence in weak external field configurations.

More recently, the importance of small, 3-dimensional error fields to tokamak configurations has become clear and theoretical methods developed for exploiting quasi-symmetry principles in stellarators are proving useful in understanding tokamaks. This time tokamaks are enjoying the benefits of theory developed principally for stellarators.

A crucial difference in energy confinement physics separates the first class of strong external field toroids from the second of weak external field toroids. Tokamaks, stellarators, and spherical tori are characterized by the presence of small scale, predominantly electrostatic plasma turbulence, which creates turbulent heat fluxes. Much experimental time and theoretical analyses have been expended on understanding this transport. Energy confinement in Class 2 configurations is historically appreciably poorer than Class 1 configurations and is governed by magnetic fluctuations. We therefore focus our attention on the generic contributions a burning tokamak plasma experiment will make to the confinement in toroids of the first class - tokamaks, spherical tori, and stellarators. The second class must make fundamental advances to eliminate or appreciably reduce transport by magnetic fluctuations in order to be considered as viable candidates for a burning plasma experiment. Tokamaks, spherical tori, and stellarators simply stand as examples that this can be done with an externally imposed confining magnetic field.

F. Generic Science Issues

Other sections of this report make it clear that a tokamak BPX will encounter operational physics conditions that are inaccessible in present machines. Among the most prominent of these is the scaling of energy confinement, which is governed by the normalized gyroradius

$$\rho^* \equiv ion\ gyro\ radius\ /\ plasma\ minor\ radius$$

whose value is smaller by roughly a factor-of-4 in planned burning plasma experiments. In terms of present day experiments, confinement is comparable in existing large tokamaks and the Japanese LHD stellarator, suggesting a common confinement physics and scaling. Thus, it seems quite reasonable that planning for a burning stellarator experiment would be based on energy confinement scaling data from a burning tokamak, but normalized to agree with stellarator experiments. Confinement in tokamaks also depends on the internal poloidal field and plasma cross-sectional shape while for the LHD stellarator it is the imposed poloidal field that affects confinemement. Again, we find a fundamental phenomenology - fine scale turbulent transport - is generic to Class 1 toroidal devices with high external fields, but that the specifics of how to minimize such transport differ among the various approaches. However, a common experimental methodology, that of finding the confinement response to scans of externally controllable parameters, shapes, and current profiles, a methodology that has long been utilized by tokamak experimentalists, has also proven rewarding for LHD. Further studies of the microscopic processes may even identify common detailed processes but this research is not sufficiently developed as yet to lead to definitive conclusions.

Interesting and scalable new physics will also emerge from studies of the interaction between energetic particles and MHD in burning plasma experiments. TAE modes, sawteeth, and other low mode number macroscopic activities are all affected by energetic particles arising either from fusion alpha particles or auxiliary heating, or both. Tokamak burning plasma experiments will result in a rather wide range of alpha particle concentrations, depending on the core temperature, which can be increased by auxiliary heating power. Auxiliary heating can also directly contribute additional energetic particles (NBI and ICRF) or simply heat core electrons (ECH) to increase the density of the fusion alpha particles. The internal magnetic profile can also be varied. A rich and extensive phenomenology will be available for exploration. For example, it would be interesting to learn whether the long magnetic diffusion times of a burning plasma experiment do indeed result in sawtooth period on the order of *15-30 sec* in ITER-FEAT, which is much longer than the energy confinement time. Based on the rather detailed correspondence that already exists between theory and observation, especially for TAE modes, one can again anticipate that data from a burning tokamak will form a strong basis for projecting stellarator and spherical torus alpha particle phenomenology. But this expectation rests on the development of sophisticated understanding and on codes that not only replicate tokamak burning plasma observations but also accommodate the fully 3-dimensional aspects of stellarator configurations.

A major success of the tokamak research has been the ability to produce detached divertor plasmas wherein plasma radiation (controlled by deuterium and impurity gas puffing), and plasma recombination (controlled by deuterium puffing), remove most of the heat outflow before it reaches the divertor strike plates. One notes that a magnetic separatrix plasma boundary, and hence a divertor, appears required for H-mode operation which in turn gives sufficient core confinement to support reasonable Q-values for the proposed tokamak burning plasma studies. A difficulty exists in projecting this edge plasma physics to burning plasma conditions in tokamak BPX or to stellarators where the magnetic topology at the plasma boundary can be quite complicated. Evidently, one must rely on plasma divertor codes, validated by replicating present experimental data, as design tools to project divertor plasma properties in burning plasma experiments. These codes contain the fundamental and nonlinear interactions of plasma-surface physics, plasma recombination, and radiation physics as well as both parallel and cross-field diffusion of particles and heat. The physics of cross-field diffusion for divertor plasmas is poorly known and constitutes a substantial uncertainty; recent modeling can be applied both to tokamak and non-tokamak plasmas. With reasonably assumed values for cross-field transport, these codes do find detached divertor solutions for ITER-FEAT and are expected to find similar solutions for FIRE.

For extrapolations to a burning spherical torus or stellarator divertor, the ability of the codes to replicate the divertor of a tokamak burning plasma will constitute an essential code validation effort. This process has already started: The US edge physics community and the German Wendelstein 7AX edge physics group are collaborating on a *3-D* edge code (BORIS) for stellarators. This code includes the nonaxisymmetric geometry; it adds much of the physics in the existing B2 and UEDGE divertor codes as well as the advanced numerical techniques contained in UEDGE, and already largely benchmarked against tokamak experiments. As the tokamak physics is upgraded to include burning plasma effects, this collaborative code will provide a basis for extending the new understanding to interpretive modeling and predictions in a burning plasma stellarator.

It is interesting and challenging to divertor codes that the three burning plasma experiments, that are the current candidates, approach the divertor rather differently. ITER-FEAT retains the original ITER philosophy that the divertor region of a burning plasma experiment needs the flexibility represented by a large, single-null divertor chamber with long divertor legs, high baffling, flexible pumps, and readily replaceable hardware. This approach limits the main plasma shaping to one with low triangularity (which is not optimal for achieving high β). It also has significant cost implications. FIRE proposes a double null configuration with appreciable heat fluxes limited to the outside layers, short divertor legs, and limited baffling. Divertor flexibility is decreased but core shaping allows larger triangularity and concomitant improvements in confinement and β. IGNITOR has no divertor at all, counting on mantel radiation to accommodate the heat flux and on adequate confinement in the core without an H-mode edge pedestal. The choice of device for a burning plasma experiment will thus have consequences for future understanding of edge and divertor physics.

In any event one can conclude that complex, sophisticated edge divertor and limiter codes are needed both to project to a tokamak burning plasma experiment and to interpret the results of burning experiments for other generic toroids, including the weak external field concepts. Planning and support for such code development should be part of any burning plasma initiative.

Consider next the issue of heating and current drive. An important and far-reaching success of generic fusion energy research has been the development of the scientific basis for radio-frequency heating and current drive methods. Positive experimental results have led to a family of sophisticated and experimentally validated codes that describe antennas, wave propagation, and wave-plasma interactions. These codes were originally developed for tokamaks. But now, stellarator and spherical tori scientists rely on evolved versions of the codes specialized to a specific plasma configuration. Radio-frequency -plasma interactions form the basis for a substantial component of advanced tokamak research on both contemporary plasmas and on a BPX.

Lastly, let us turn to steady state tokamak burning plasma experiments. Steady state is a key objective of the U.S. Advanced Tokamak program. Discharges will involve the coupled transport of heat, poloidal flux, particles and angular momentum as well as generation of plasma current by the bootstrap effect. Such AT plasmas, with close to 100% bootstrap current and self-consistent profiles, can be readily formed, given sufficient auxiliary heating power. Remaining questions include: “What β can be stably attained and how can the profiles be altered?” Definitive discharges that last many current relaxation times are needed and are not accessible by present devices, and in fact are only marginally accessible in the proposed BPX candidates. Burning plasmas are likely to generate yet a new set of physics challenges for advanced tokamaks. This data can be directly applied to a steady-state spherical torus. Stellarators are of course steady-state from the outset.

In summary, any burning plasma experimental program should include, in addition to the main experimental device, a strong science program with the following components. (a) An infrastructure designed to extract the science from the experiment, including a set of radiation-hardened diagnostics capable of measuring the spatially and temporally resolved plasma parameters underlying the important physics issues. (b) A coordinated theory and code development program whose objective is two-fold: projecting performance for the experiment and validating codes to understand the implications of burning plasma experimental data to other configurations. Specifically, the results should be applicable to Class 1 generic strong external-field toroids and, albeit to a lesser extent perhaps, to improved versions of Class 2 weak external field toroids. Planning for these elements should be included early in the scientific scoping of the experiment, recognizing that they will have a large impact on the generic applicability of results in the burning plasma regime.

The discussion presented here suggests that there are a sufficient number of issues in a tokamak based BPX that are generic to other configurations, that it makes good scientific sense to proceed with such an experiment. A tokamak BPX would not be overly specialized. The specific choice of tokamak BPX involves a multi-space cost benefit analysis, of which the generic aspects are only one component. Selecting from among the three options requires a further study beyond the scope of this report.

IV. Burning Plasma Experiments: Performance Projections and Science Goals

A. Summary of Critical Issues and Critical Parameters

Section III presented a discussion of the general science issues that would arise in a next generation burning plasma experiment. In this section, these issues are discussed in the context of actual existing experiments as well as the three primary burning plasma experiments currently under consideration, ITER-FEAT, FIRE, and IGNITOR. It is shown by comparisons with specific existing experiments, that such experiments can address some of the burning plasma issues either in isolation or under reduced performance conditions. However, they cannot simultaneously address the multiple issues and the corresponding nonlinear coupling that is expected to arise in the strong self-heated regime.

A detailed comparison of the general issues with respect to each of the three proposed burning plasma experiments is also carried out. As previously stated, the size and cost of these three devices varies by about an order of magnitude and thus a wide range of capabilities and scientific studies are possible. Even so, when examined in detail each of these devices is shown to be potentially capable of greatly extending our current knowledge base well into the regime of burning plasma physics and would thus represent a major scientific accomplishment. The ultimate first choice of device then requires a careful cost/benefit analysis.

In making the connections between the burning plasma science issues and existing and future experiments it is useful to summarize the critical parameters required to address each of these issues as discussed in Sec. III. For the MHD equilibrium and stability issues the critical parameters are normalized beta β_N, pressure p, safety factor q^*, and density normalized to the Greenwald density n/n_G. The critical parameters determining the amount and type of externally supplied heating and current drive power are the desired operating temperature T, current I, plasma volume V, and bootstrap fraction f_B. For transport behavior the critical parameters are as follows: the required energy confinement time τ_E, the fusion performance parameter $p\,\tau_E$, the fraction of losses made up by alpha heating f_α, and high-mode enhancement factor H. Many of these parameters are also critical to study new alpha particle effects. An additional critical parameter is the normalized alpha particle pressure β_α. In terms of pulse length the parameter of interest is the ratio of pulse length to current diffusion time τ_{pulse}/τ_{CR}. Lastly, for issues related to plasma-boundary interactions the critical performance criteria are not actually related to specific numerical parameters, but instead to experimental capabilities. These include divertors vs. limiters, pumping capacity, and flexibility in fueling methods.

Using this summary, the report now attempts to assess the capabilities of existing experiments and future proposed experiments with respect to burning plasma issues.

B. Science Basis for Projecting Burning Plasma Performance

The scientific basis for a tokamak burning plasma experiment has been obtained largely from the operation of a number of tokamaks over the past decade. The development of increasingly sophisticated plasma diagnostics, capable of measuring nearly all the relevant plasma parameters, has been a major accomplishment of the fusion program over the past two decades. The data from these diagnostics in conjunction with theory and computer simulations have provided the scientific understanding for projecting the performance of a burning plasma experiment, and have identified the issues that need to be addressed in a next step burning plasma experiment. Present tokamak experiments are capable of producing plasmas where nearly all of the plasma physics parameters, considered individually, approach or even exceed those expected in a reactor, both in absolute and dimensionless terms, as shown in Table 1[1]. This gives confidence that the physics understanding of confinement, MHD stability, wave particle interactions and boundary physics derived from the present tokamak experiments will be relevant to a burning plasma experiment.

Table 1. Parameters in Present Experiments (not achieved simultaneously)

	Present Tokamaks	ARIES Tokamak Plant
Core Plasma Physics		
fuel density, $10^{20}\ m^{-3}$	5	2
temperature, *keV*	20	15
plasma pressure, *atm.*	3	10
normalized radius, $1/\rho_i*$	300	1000
normalized collision freq. $\nu*$	0.01	0.01
β, %	10	5
Boundary Physics Parameters		
Ploss/R, MW/m	5	75
Fusion Plasma Parameters		
$n_i(0)\tau_E Ti(0)$, $10^{20}\ m^{-3}$ s keV	4 - 8	60
$p(0)\tau_E$ atm-sec	0.6 – 1.2	10
self-heating, f_α	0.1	0.8
Plasma Duration τ_{pulse}/τ_{CR}	2-10 sec	Steady-state

However, as stated, not all plasma parameters characterizing the core of a fusion plasma have been produced simultaneously so that the full range of fusion plasma interactions has not been accessed. The most notable short falls are in $1/\rho_i*$, the number of ion gyro orbits across the confinement region and in the performance parameters P_{loss}/R and $n\tau_E T$, the latter being equivalent to $p\tau_E$. In particular, the parameter $1/\rho_i*$ is important in determining plasma

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[1] Two quantities, not yet carefully defined, have been introduced in the table. These quantities are not essential to the discussion but are widely used in the fusion community and thus are included for completeness. The first is $\nu*$ a measure of the plasma collisionality defined as the ratio of the electron Coulomb collision frequency for de-trapping particles to the mirror frequency of trapped electrons in a toroidal magnetic field. The second is the triple product $nT\tau_E$ which is equivalent to $p\tau_E$ except the units are different.

confinement, which is critical for obtaining high fusion self-heating. Increasing $1/\rho_i*$ requires an experiment with higher magnetic field and/or larger size compared to present tokamak facilities.

The boundary edge of a fusion plasma merges high temperature plasma physics with atomic and molecular physics under high power density conditions. The boundary conditions reflected back into the plasma have profound effects on core plasma confinement, in agreement with current understanding of plasma transport based on marginal stability of microturbulence. At the same time, efficient transfer of the power and particle exhaust requires boundary conditions that conflict with core plasma requirements, and therefore cannot be modeled or simulated in the absence of the core plasma. One characterization of the plasma boundary is the power loss from the core plasma normalized to the major radius, $Ploss/R$, which will increase by a factor ~ 10 from present experiments to a power plant plasma.

The fusion parameters achieved in present experiments, while achieving the goals set for those experiments, are only about 10% of those required by a fusion power plant plasma. This is illustrated in the Lawson Diagram, Figure 4, for the Lawson parameter, $n_i \tau_E T_i$. Transient Lawson parameters within a factor of 6 of that needed for $Q \approx 10$ have been attained. However, the Lawson parameters for plasmas sustained for $\sim 10\ \tau_E$ are a factor of ~ 25 below that required for a fusion plasma. A major requirement for a burning plasma experiment is to be able to produce a plasma with an $n_i \tau_E T_i$ sufficient to access burning plasma conditions, and to have the

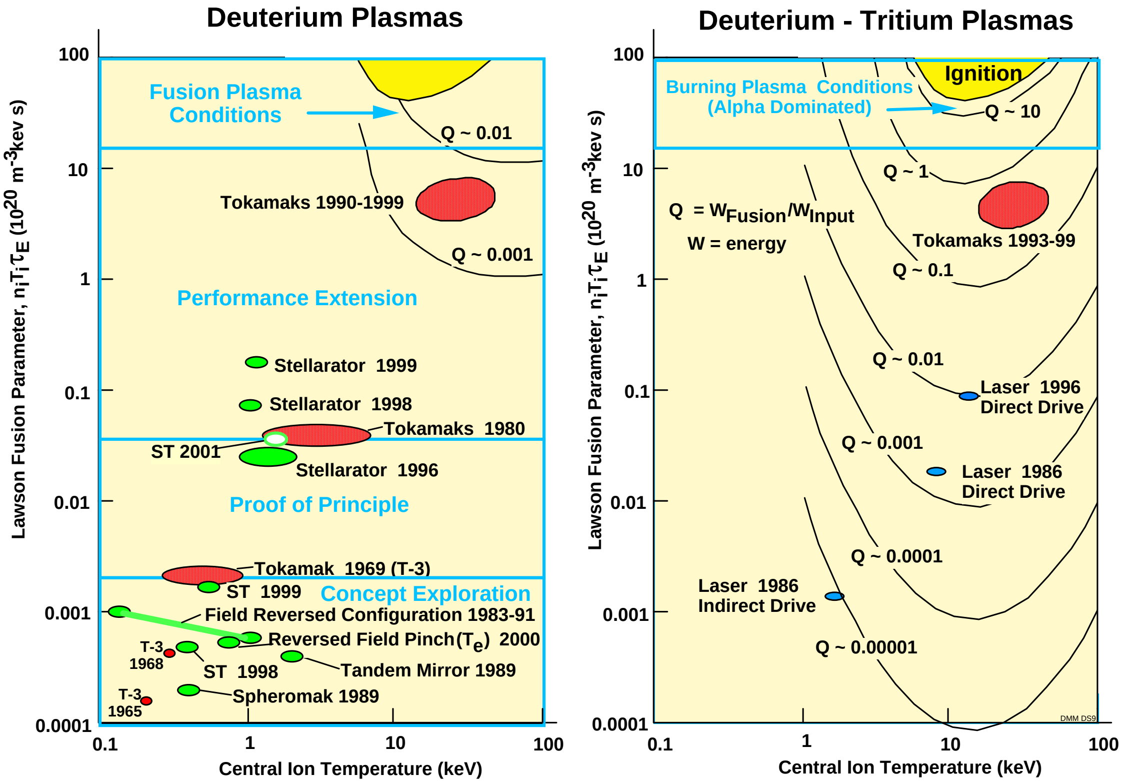

Figure 4 Lawson diagram illustrating progress and requirements for a burning plasma. Shown are diagrams for deuterium plasmas and deuterium-tritium plasmas.

experimental flexibility to explore and understand the conditions necessary to attain burning plasma conditions.

Experiments on TFTR and JET have studied weakly burning *D-T* plasmas where the self-heating, while small ($f_\alpha < 0.1$), was observed in accordance with expectations. The energetic alpha particles produced by the *D-T* fusion reaction were observed to be confined and to transfer energy to the plasma in agreement with theoretical models. No energetic alpha induced instabilities were observed under standard conditions. When the plasma conditions were modified as suggested by theory, small amplitude alpha induced instabilities were observed as predicted. In a fusion plasma all these effects will be stronger and the alpha heating will dominate the evolution of the temperature and pressure of the plasma. This complex non-linear interaction is the essence of a fusion plasma, and requires a new facility capable of burning *D-T* fuel with size and magnetic field well beyond the upgrade capability present tokamaks.

A burning plasma experiment will require burning plasma conditions that are sustained for a duration long ($\sim 10\ \tau_E$, several τ_H and a few τ_{CR}) compared to the intrinsic plasma time scales.

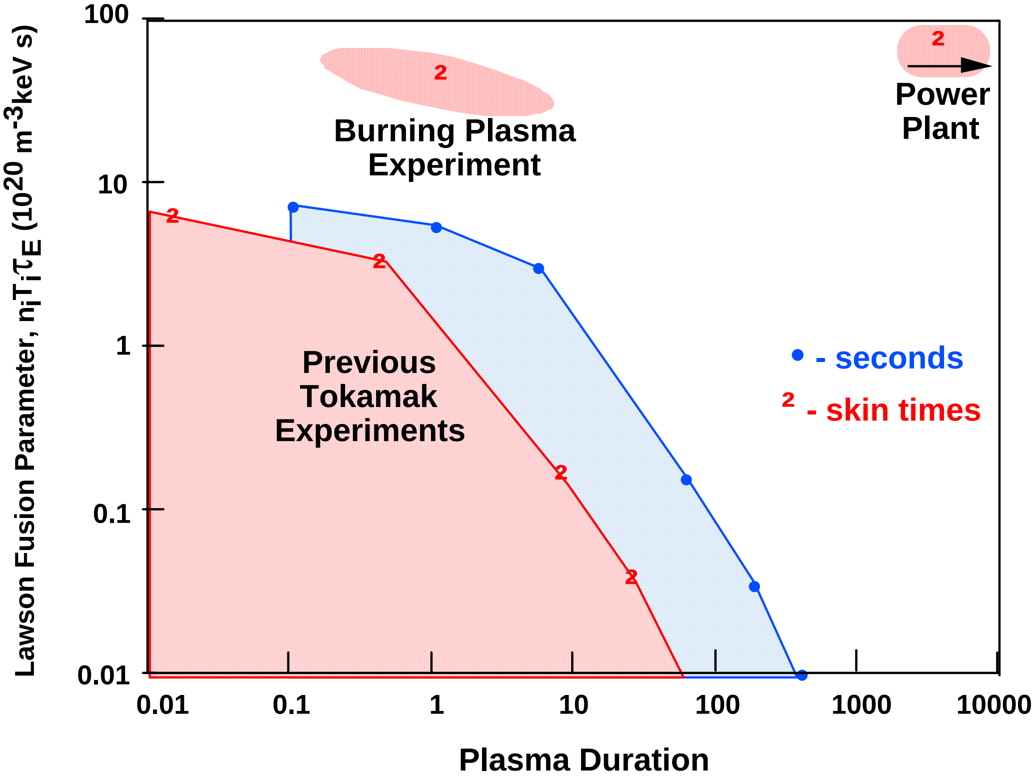

Figure 5 Plasma duration of present tokamak experiments compared with requirement for a burning plasma and power plant.

This requirement far exceeds the capability of the present tokamak experiments as shown in Figure 5. Good progress has been made over the last several years to sustain modest performance plasmas for pulse durations up to $\sim 10\ \tau_E$ (approaching one current diffusion time) providing further confidence for designing a burning plasma experiment. The overall basis for designing a burning plasma experiment with reasonable confidence is now in hand. During the next several years the base program will continue to improve our understanding of detailed design issues particularly in the area of advanced tokamak regimes. However, it will not be possible to access burning plasma conditions without a new major facility.

field well beyond the upgrade capability present tokamaks.

A burning plasma experiment will require burning plasma conditions that are sustained for a duration long (~ 10 τ_E, several τ_{He} and a few τ_{skin}) compared to the intrinsic plasma time scales. This requirement far exceeds the capability of the present tokamak experiments as shown in Figure 5. Good progress has been made over the last several years to sustain modest performance plasmas for ~ 10 τ_E (one skin time) providing a basis for designing a burning plasma experiment.

The overall basis for designing a burning plasma experiment with reasonable confidence is now in hand. During the next several years the base program will continue to improve our understanding of detailed design issues particularly in the area of advanced tokamak regimes. However, it will not be possible to access burning plasma conditions without a new major facility.

C. Science Goals of Proposed Burning Plasma Experiments

There are presently three major burning plasma experimental designs under consideration or under development worldwide: ITER-FEAT being developed by the European Union, Japan, and Russia; FIRE being developed in the U.S.; and IGNITOR being developed in Italy. These vary widely in overall mission/objectives, design philosophy, schedule, performance, and costs, with ITER being the largest (single step to DEMO) endeavor and IGNITOR the smallest in terms of both size and cost. ITER is a large device with superconducting magnets, while FIRE and IGNITOR are more compact, higher field devices with copper magnets. ITER and IGNITOR have received the most extensive design effort to date, FIRE the least. Although each device would deliver different amounts of scientific information, any of the three facilities would deliver a large and significant advance in our understanding of burning plasmas.

This sub-section contains a description of these three designs, listed in the order from smallest to largest: IGNITOR, FIRE and ITER-FEAT. These descriptions represent the proponents' view, as best as we could ascertain, and include the basic parameters (Tables 2 and 3)[2], the primary

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[2] Tables 2 and 3 contain several new symbols not as yet accurately defined. These are by and large closely related to the simpler quantities introduced in the text and are used widely in the community. They are as follows. The quantity q is a measure of the local pitch angle of the magnetic field; that is q is a function of minor radius. The value of q at the plasma edge, q_a, is closely related to the quantity q^* in plasma without a divertor. In plasmas with a divertor one typically uses q_{95} representing the value of q on the magnetic surface containing 95% of the total poloidal magnetic flux. Typically, one requires q_a or q_{95} to be greater than 3 to avoid a large sawtooth region. The quantities κ_x and κ_{95} represent the elongation of the plasma - the ratio of height to width - at the X point of the separatrix and the 95% surface. Similarly, δ_x and δ_{95} represent the triangularity of the plasma - the horizontal distance from the maximum plasma height to the geometric center of the plasma at $R = R_0$ - normalized to the minor radius a. The quantities β_{tor} and β_{pol} are the toroidal and poloidal beta of the plasma defined as the ratio of the volume averaged pressure to the toroidal and poloidal magnetic pressure respectively. Finally, the quantities *H89-P*

scientific goals, and some of the advantages and disadvantages of each proposed burning plasma experiment. We emphasize that the panel has not had time to carefully scrutinize and check each and every piece of information contained within the tables. This information originates from each of the individual design teams, who, unfortunately, sometimes use slightly different definitions for certain parameters. Thus, not all the data is completely self-consistent. Even so, the information presented does present a reasonably accurate overall description of each device, which is useful for an approximate comparison. One goal of the proposed 2002 Snowmass summer study, described in Sec. VI, is to improve the accuracy, self-consistency, and uniformity of the device descriptions.

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and *H(y,2)-IPB98* are the *H* factors for two of the empirical scaling relations derived from various sets of data in the tokamak data base that should be reasonably reliable for a BPX experiment.

Table 2. Dimensional [engineering] Parameters of Burning Plasma Experiments [Q=10 case]

Parameters	G. ym bol	H. nit	I.	FIRE	ITER
Major/minor radius:	R/a	m/m	1.32/0.47	2.14/0.595	6.2/2.0
Elongation (X-point/95%flux)	κ_x/κ_{95}		κ_a= 1.83	2.0/1.81	1.85/1.70
Triangularity (X-point/95%flux)	δ_x/δ_{95}		δ_a= 0.4	0.7/0.4	0.49/0.33
Plasma volume	V_p	m^3	10	26	837
Plasma surface area	A_p	m^2	34	67	678
Configuration		—	Extended limiter	DN divertor	SN divertor
Number of toroidal field coils	N	—	24	16	18
Toroidal magnetic field ripple	$\delta B/B$	%	<1.5	0.3	0.5
Toroidal magnetic field	B (at $R = R_O$)	T	13	10	5.3
Plasma current	I	MA	11	7.7	15(17.4)
Kink safety factor	q^*		1.81	1.94	1.94(1.68)
Safety factor (95% flux or edge)	$q_\psi(95\%)$		q_a=3.5	3.05	3.0(2.6)
Ion temperature	$T_i(0)$	keV	10.5	11	19
Ion temp. /Electron temp.	T_i / T_e		~1	~ 1	~ 1
Temperature profile peaking	$T(0)/\langle T\rangle_n$		2	1.7	1.7
Electron density	$n_{e20}(0)$	$10^{20}\ m^{-3}$	10	5.5	1.0
Density profile peaking	$n_e(0)/\langle n_e\rangle$		2	1.2	1.1
Line average density/Greenwald	$\langle n\rangle_l/n_G$		0.4	0.7	0.85
Plasma Energy (inc. alphas)	W_p	MJ	12	38	320
Required energy confinement time	τ_E	s	0.6	1.0	3.7
Fusion triple product (core)	$T_i(0)n_{i20}(0)\tau_E$	$10^{20}\ keV\ m^{-3}\ s$	63	52	74
Fusion triple product - $p\tau$	$p(0)\tau_E$	atm-sec	10	8.3	12
Fusion Power Gain	$Q = P_f/P_{heat}$		10	10	10
Fusion Power	P_f	MW	100	150	400
Auxiliary Power Installed	P_{aux} or P_{CD}	MW	18-24	20 (30)	73(130)
Pulse length (inductive) Normalized pulse length	τ_{pulse} τ_{pulse} / τ_{CR}	sec	4 1.1	20 1.5	400 2

(upgrades/second phase)

The parameters for ITER and FIRE are typical values calculated using a *0-D* steady state power balance with alpha heating and alpha ash buildup calculated self-consistently for a $Q = 10$ scenario. In this model, the required confinement time is determined from the power balance and is then compared with empirical scalings derived from the International Confinement Data Base as described in the ITER Physics Basis, Nuclear Fusion Vol. **39**, no. 12, p 2208, 1999. The parameters for IGNITOR were calculated using a 1-D JETTO code for an ohmically heated case.

Table 3. Dimensionless Parameters Describing Physics Performance in Burning Plasmas

Parameters	Symbol	Unit	IGNITOR	FIRE	ITER
Base Burning Plasma Mode [*Q=10 case*]					
Normalized collisionality ν^* @ $a/2$			0.043	0.058	0.045
Normalized size (a/ρ_i)	$1/\rho^*$		390	352	483
Normalized pressure (beta tor.)	β_{tor}	%	1.2	2.4	2.6
Normalized pressure (beta pol.)	β_{pol}		0.2	0.72	0.62
Normalized beta $\beta_{tor}/(I/aB)$	β_N	%	0.7	1.84	1.81
Normalized density	$\langle n\rangle_l / n_G$		0.4	0.7	0.85
Confinement relative to L-Mode	*H89-P*		1.5	2.6	2.0
Confinement relative to H-Mode	*H(y,2)-IPB98*		0.6	1.1	0.99
Loss power / H-mode threshold	$P_{loss}/P_{L\text{-}H}$		NA	1.3	2.4
Helium Ash pumping			No	Yes	Yes
Effective Helium Ash confinement	τ_{He} / τ_E		>5	5	5
Impurity content	Z_{eff}		1.2	1.41	1.7
(Alpha /Total) plasma heating	f_α		0.67	0.67	0.67
Alpha heating/power losses	P_α/P_{losses}		1	0.67	0.67
Alpha beta	β_α	%	0.05	0.15	0.34
Alpha instability driving term	$R\,\nabla\beta_\alpha$		0.02	0.039	0.077
Normalized alpha particle velocity	$v_\alpha/v_{\text{Alfvén}}$		1.6	2	1.6
Advanced Tokamak (AT) Mode(*)			Reverse shear	AT	AT
Toroidal magnetic field	B (at $R=R_o$)	*T*	12	8.5	5.3
Plasma current	I	*MA*	7	5.5	9.1
Safety factor (at 95% flux)	$q_\psi(95\%)$, q_{95}		4.9	3.6	5.0
Minimum q	q_{min}		1.5	2.2	3.0
Minor radius corresponding to q_{min}	r_{min} / a		0.4	0.8	0.7
Current drive	*LH/ECH/ICH*	*MW*	0	(LH: 20)	40/20/00
(Bootstrap/Total) current	f_B		~ 0.2	0.64	0.4
Normalized beta	β_N		1.1	3.0	2.8
Res. wall mode number stabilized	*n (mode num)*		None	1	1
Confinement relative to H-mode	*H(y,2)-IPB98*	*T*	1.1	1.6	1.4
Fusion gain	$Q = P_f/P_{heat}$		~ 7.5	7.5	5.0
Pulse length Normalized pulse time	τ_{pulse} τ_{pulse} / τ_{CR}	*sec*	~ 5 ~ 1	35 ~ 1.5	>3000 >10

(*) AT mode parameters are examples of some representative cases that are available at this time. These are under active development by all teams. Some values supplied by the panel.

IGNITOR, A Compact High-Field Ignition Experiment

Mission

IGNITOR's mission is to gain access to ignition regimes through a conservative approach. In view of the uncertainties surrounding the physics of and the access to burning plasma regimes, IGNITOR [1] could provide a test bed for burning plasma experiments at low cost and low risk. Indeed, the major strengths of IGNITOR reside in the wide safety margins with respect to MHD stability, density limits and alpha particle driven modes, all of which pose serious threats to the achievement of ignition. With respect to MHD stability, the IGNITOR plasma [2] is designed to achieve burning conditions with a normalized beta β_N of 0.67, which is well below the stability threshold of dangerous MHD instabilities such as the Neoclassical Tearing Mode and Resistive Wall Mode requiring $\beta_N \geq 2$ and $\beta_N \geq 3$, respectively. Furthermore, IGNITOR's [1] high edge safety factor $(q_a = 3.6)$ combined with low poloidal beta $(\beta_p \approx 0.26)$ simultaneously limits the size of the $q = 1$ surface, the coupling to the $m = 2$ harmonic and the ideal MHD drive for the internal $n = 1$ kink, thus reducing the detrimental effects of sawteeth on energy and alpha particle confinement. Though its plasma density is large, IGNITOR is designed to operate well below the Greenwald density limits [1-3] $(n \approx 0.4n_G)$ thereby avoiding the degradation in confinement that is likely to occur when operating close to the density limit. In the standard mode of operation, IGNITOR's plasma is expected to be free of alpha-particle-driven Toroidal Alfven Eigenmodes (TAEs) as its low ion temperature limits the size of the alpha particle pressure (which drives the instability), and the high plasma density enhances the stabilizing effects of the ion Landau damping.

Machine description and operational regimes

IGNITOR is a high field, copper magnet, compact tokamak along the lines of the ALCATOR A, C and C-Mod devices at MIT, as well as the FT and FTU tokamaks at ENEA-Frascati (Italy). IGNITOR proponents claim that ignition conditions can be reached in the standard mode of operation [1]: L mode, ohmic, $B(R_o) = 13\ T, I = 11\ MA, R = 1.32\ m, a = 0.47\ m, \kappa = 1.83,$ $<n> = 5x10^{20}\ m^{-3}, T_{e0} \approx T_{i0} \approx 11\ keV$. Because of its high magnetic field and the absence of a divertor, the size (and therefore the cost) of IGNITOR is significantly less than the cost of present and past large MFE experiments (JET, TFTR, W7-X). The plasma volume of IGNITOR is only $10\ m^3$ and its construction cost is estimated to be in the range of \$250M. (This cost is based on an Italian study using their accounting procedures.) Another strength of IGNITOR is the high plasma purity expected in its high-density plasma [1]. This leads to an effective charge for impurities given by $Z_{eff} \approx 1.2$ (a plasma with zero impurities has $Z_{eff} = 1$). The cold radiative mantle solution with a molybdenum first wall proposed for IGNITOR should be able to dissipate most of the power losses without appreciable confinement degradation. The power losses should be spread uniformly over the first wall, which plays the role of a distributed limiter. IGNITOR is also well suited [1] for a Reversed Shear Mode of operation, at a lower current $(7MA$ and $12T)$ and higher edge safety factor, aided by a modest amount of additional ICRF power (the design includes $20\ MW$ of RF heating). Burning plasma regimes in the Reversed Shear Mode can be accessed if the energy confinement enhancement factor induced by an internal transport barrier is in the range of $H \sim 2.5\text{-}3$. H modes should be realizable in IGNITOR as the power input is well above the H mode threshold and X-point configurations can be generated through its flexible poloidal field systems. The IGNITOR cross-section is shown in Fig. 6.

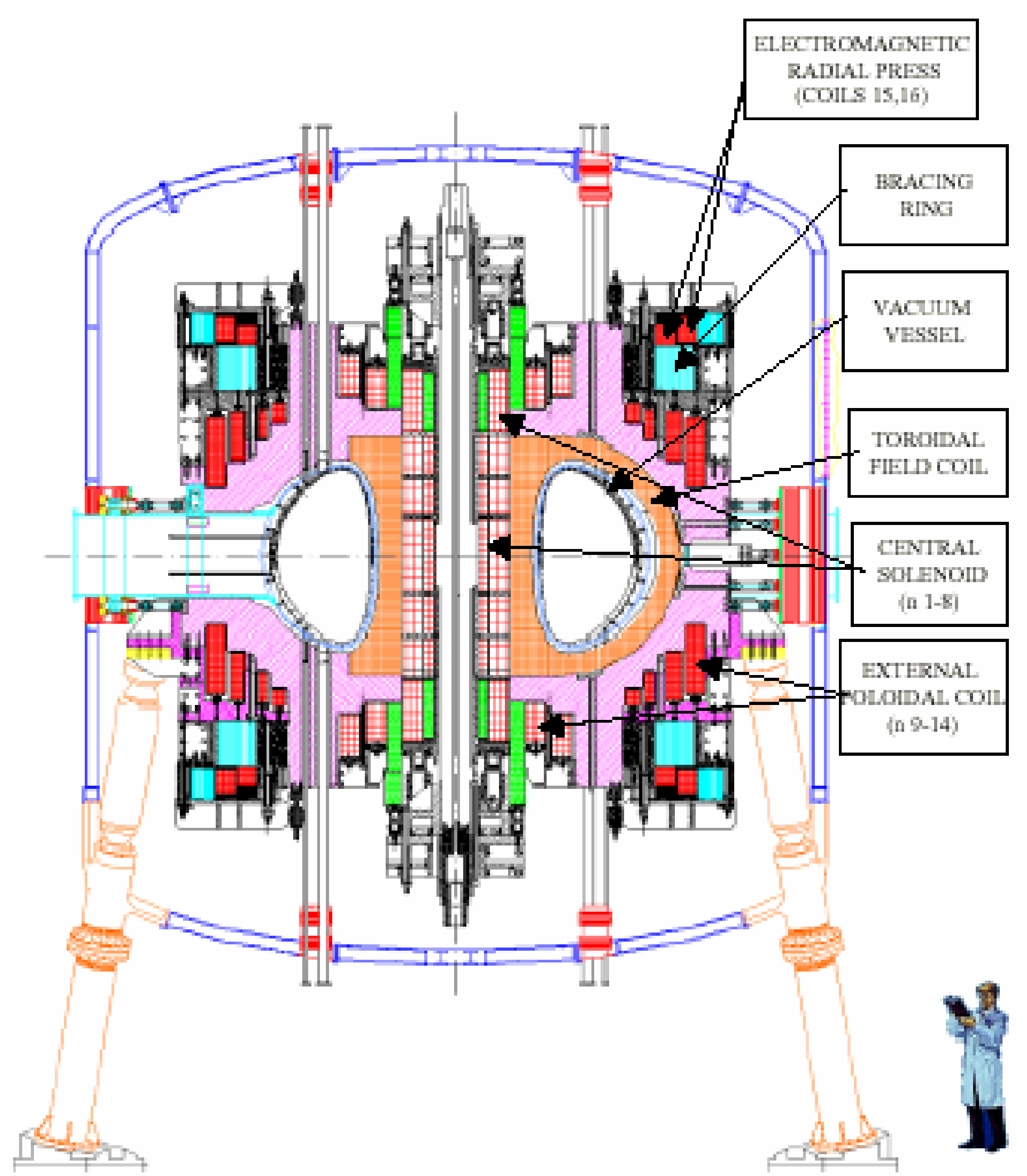

Figure 6 IGNITOR cross-section

Plasma Performance and Assessment (advantages/disadvantages)

The IGNITOR confinement time, τ_E, required for ignition [1] in the standard mode of operation is slightly above $0.5\ s$ corresponding to a thermal diffusivity of $0.2\ m^2/s$. Similar values of the diffusivity (approximately $0.13\ m^2/s$) have been achieved during L-mode operations in Alcator C with peaked density profiles. However, the projections of IGNITOR confinement time are subject to different interpretation [2] as might be expected when dealing with unresolved physics issues such as anomalous energy transport. IGNITOR proponents claim [1] that density peaking is beneficial but not essential as long as τ_E stays above $0.5\ s$ for $T_0 \approx 11\ keV$ and the density peaking factor varies from *0.5 to 2*. Furthermore, IGNITOR is predicted [1] to ignite at higher temperatures $(T_0 \approx 14.5\ keV)$ by adding auxiliary power in the event the confinement time is reduced by a factor of *2/3* to $0.37\ s$. A recent analysis of confinement times for high-density L-mode discharges of the ITER-97P database $(0.5 \leq \langle T_i\rangle/\langle T_e\rangle \leq 2.0,\ \langle n_e\rangle \leq 0.5n_G$, see [4,5]) shows a projected confinement time of $0.6\ s$ for IGNITOR. An opposing evaluation was recently provided in the TTP report [2] indicating that standard L mode scaling expressions such as ITER-97P and ITER-89P predict IGNITOR confinement times of $0.47\ s$ and $0.37\ s$, respectively, suggesting that an enhancement factor ranging from *1.3* to *1.6* is required to reach the value of $0.6\ s$. However, the authors of [2] also recognize that significant enhancement factors (> 1.4) with respect to standard L-mode scaling have been routinely achieved in several tokamaks depending on the density profile peaking. Peaked density profiles can be realized in IGNITOR through fast pellet injection though some questions still remain with regards to the improvement in the injection technology required for high temperature and high-density plasmas. IGNITOR proponents claim [6] that an outside launch with an injection velocity of $4\ km/s$ is sufficient to provide the necessary pellet penetration depth and that such velocities are within reach of the current pellet injection technology.

Although the simple demonstration of ignition is, without argument, a remarkable accomplishment for a burning plasma experiment, a more compelling case can be made for those devices that are capable of exploring burning plasma physics in a variety of regimes and time scales. The essential time scales for a burning plasma experiment are the alpha particle slowing-down time $\tau_{s\alpha}$, the pulse length τ_{pulse}, the energy confinement time τ_E, and the current redistribution time τ_{CR}. Even though IGNITOR is capable of achieving ignition (i.e., the plasma state where $P_\alpha = P_l$), it does so in the presence of a substantial ohmic power. The relevance of a burning plasma to a reactor operation can be measured by comparing the relative magnitude of the different time scales as well as the magnitude of the ratio P_α/P_{ext} (alpha heating power/total input power). IGNITOR is characterized by an energy confinement time substantially larger than the alpha slowing-down time $(\tau_E/\tau_{s\alpha} \sim 11)$ and a ratio P_α/P_{ext} of about *2* (corresponding to $Q = 10$) indicating operation in the strong alpha heating regime. It is important to note that the alpha heating in IGNITOR is purposely maintained low to reduce the neutron production. Indeed, IGNITOR could reach larger values of P_α/P_{ext} as indicated in the simulations of [7] where $P_\alpha/P_{ext} \sim 4.3$ *(i.e.* $Q > 21)$ after $t = 5\ s$ and $P_\alpha/P_{ext} = 10$ (i.e. $Q = 50$) at $t = 9\ s$. Another desirable property in a burning plasma experiment is the long-pulse capability measured by the ratio τ_{pulse}/τ_{CR}. The larger this ratio, the greater is the resemblance to steady state operation. Similar to the other proposed burning plasma experiments, IGNITOR does not operate in a true steady state with $\tau_{pulse}/\tau_{CR} >> 1$, instead $\tau_{pulse}/\tau_{CR} \sim 1.1$. As for the alpha ash, IGNITOR's plasma is expected to be weakly affected by ash accumulation.

It is important to emphasize that all the parameters reported above are related to the standard mode of operation, which is an L-mode, ohmic regime. H-modes could also be accessed in IGNITOR. However, if the X-points within the first wall are required to enter the H-mode, concerns about the large heat fluxes to the wall need to be considered [2]. However, as stated in [1], thermal loads on the IGNITOR "first wall tiles will be the subject of detailed analyses," and they are "not expected to be a problem." IGNITOR proponents argue [1] that the H-mode operation is far from optimal for accessing the ignition regime, as H-mode density profiles are typically flat. Thus, H-mode operation is only considered as an "interesting physics option."

In summary, the IGNITOR tokamak is a physics experiment designed to achieve ignition conditions with a wide safety margin with respect to MHD instability, alpha particle driven modes and density limits in the standard mode of operation (L mode, ohmic, $B_0 = 13\ T$ and $I_p = 11\ MA$). The energy confinement time required for ignition is slightly above $0.5\ s$ at $T_0 = 11\ keV$ and as low as $0.37\ s$ for ignition at $14.5\ keV$ with added auxiliary power. Though some discrepancies exist among the different predictions for τ_E, advocates argue that IGNITOR can access the ignition regime with a peaked density profile maintained through pellet injection.

Enhanced confinement regimes such as reversed shear modes and H-mode may also be investigated in IGNITOR by lowering the current and generating X-point configurations. In view of its smaller size, the absence of a divertor, and low tritium inventory, proponents believe that the cost of the IGNITOR facility *(~ $250M)* and its construction time *(~ 5 years)* are expected to be substantially lower than the other burning plasma experiments under consideration.

The design of IGNITOR has been greatly improved since it was first proposed twenty-five years ago [8]. Another distinct advantage of the IGNITOR concept resides in its advanced stage of development as well as in the high level of physics scrutiny delivered by several independent groups and panels [2,7]. Nevertheless, engineering and cost studies, while receiving considerable effort in Italy, need to be carried out by a U.S. team to assure self-consistency and uniformity with respect to the other BPX experiments under consideration.

The main conclusion of the IGNITOR advocates is as follows. Since prototypes of several machine components have already been built and independent assessments of the main physics issues have already been carried out [2,7], the advocates believe that IGNITOR is now ready to move forward and expeditiously through the construction process if a positive decision is taken in this direction.

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FIRE, An Advanced Burning Plasma Experiment

Mission

The mission of FIRE [1,2] is to attain, explore, understand and optimize fusion-dominated plasmas to provide knowledge for designing attractive MFE systems. Proponents envision FIRE as an extension of the existing advanced tokamak program leading to an attractive magnetic fusion reactor (e.g., ARIES-RS). The FIRE [1,2] design study of a next step burning plasma experiment has the goal of developing a concept for an experimental facility to explore and understand the strong non-linear coupling among confinement, MHD stability, self-heating, edge physics and wave-particle interactions that is fundamental to fusion plasma behavior. This will require plasmas dominated by alpha heating $(Q \approx 10)$ that are sustained for a pulse duration comparable to characteristic plasma time scales $(\geq 10\ \tau_E,\ \sim 4\tau_{He},\ \sim 2\ \tau_{CR})$. The FIRE pre-conceptual design activities, carried out by a U.S. national team, have been undertaken with the objective of finding the minimum size (cost) device to achieve the essential burning plasma science goals.

Design Description

FIRE design activities [1,2] have focused on the physics and engineering assessment of a compact, high-field tokamak with the capability of achieving $Q \approx 10$ in the Elmy H-mode for a duration of ~ 1.5 times the plasma current redistribution times during an initial burning plasma science phase. The design has the flexibility to add advanced tokamak hardware (e.g., lower hybrid current drive) later. The configuration chosen for FIRE is similar to that of ARIES-RS, namely a highly shaped plasma, with a double-null divertor and aspect ratio ≈ 4. The key "advanced tokamak" features included in the design are: strong plasma shaping, double null poloidal divertors, low toroidal field ripple $(< 0.3\%)$, internal control coils and space for wall stabilization capabilities.

The reference design point (Table 2) is $R_o = 2.14\ m$, $a = 0.595\ m$, $B(R_o) = 10\ T$, $I = 7.7\ MA$ with a flat top time of *20 s* for *150 MW* of fusion power with the cross-section shown in Fig. 7. The baseline magnetic fields and pulse lengths can be provided by a wedged BeCu/OFHC toroidal field (TF) coils and OFHC poloidal field (PF) coils that are pre-cooled to *77°K* prior to the pulse and allowed to warm up to *373°K* at the end of the pulse. *3-D* finite-element stress analyses including electromagnetic, and thermal stress due to ohmic and nuclear heating have shown that this design has a margin of *30%* beyond the allowable engineering stress. Large mid-plane ports *(1.3 m by 0.7 m)* provide access for heating, diagnostics and remote manipulators, while *32* angled ports provide access to the divertor regions for utilities and diagnostics. FIRE is being designed mechanically to accommodate *3,000* full field, full power pulses and *30,000* pulses at *2/3* field with a total fusion energy production of *5.5 TJ*. The repetition time at full field and full pulse length will be < *3 hr*, with much shorter times at reduced field or pulse length.

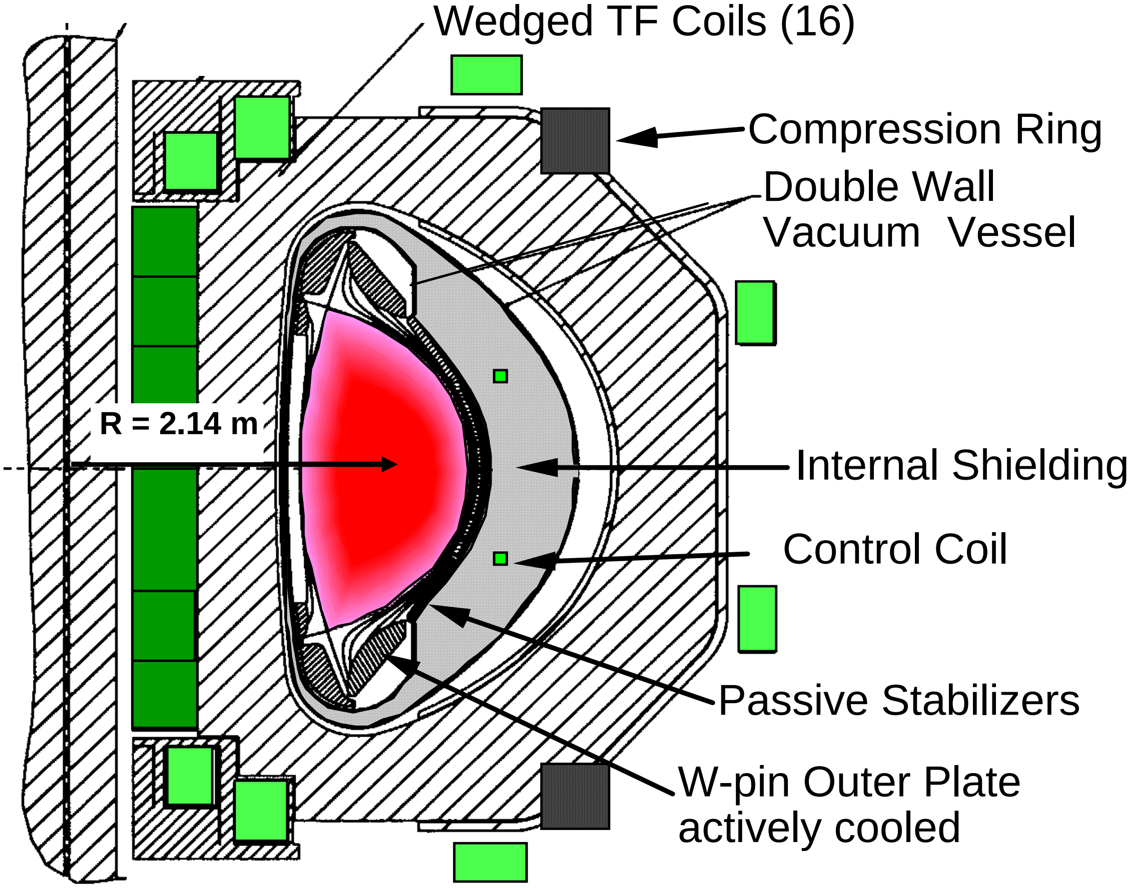

Figure 7 The FIRE configuration

Proponents note that FIRE will provide reactor relevant experience for divertor and first wall power handling because the anticipated thermal power densities on the divertor plates of ~ *6* MW/m^2 for detached operation and ~ *25* MW/m^2 for attached operation exceed present experiments and approach those anticipated for ARIES-RS. FIRE would use only reactor relevant metallic materials for plasma facing components, and carbon would not be allowed in the vessel due to tritium inventory build-up by co-deposition. The divertor plasma-facing components are tungsten "brush" targets mounted on copper backing plates, similar to a concept developed by the ITER R&D activity. The outer divertor plates and baffle are water-cooled and come into steady-state equilibrium during the pulse. The first wall is comprised of Be plasma-sprayed onto copper tiles. The neutron wall loading in FIRE is ~ *2* MW/m^2 and produces significant nuclear heating of the first wall and vacuum vessel during the *20 s* pulse. The inner divertor targets and first wall are cooled by mechanical attachment to water-cooled copper plates inside the vacuum vessel. Sixteen cryo-pumps - closely coupled to the divertor chambers but behind sufficient neutron shielding - provide pumping (≥ 100 $Pa\ m^3/s$) for *D-T* and He ash during the pulse. Pellet injection scenarios with high-field-side launch capability will reduce tritium throughput, and enhance fusion performance. The in-device tritium inventory will be determined primarily by the cycle time of the divertor cryo-pumps, and can range from < *2 g* for regeneration overnight to ~ *10 g* for weekly regeneration. The tritium usage per shot and inventory is comparable to that of TFTR and therefore will not require a large step beyond previous U.S. fusion program experience in tritium shipping and handling.

According to [1,2], the construction cost of the tokamak subsystem (magnets, divertor, plasma facing components and mechanical structure) has been estimated to be ≈ *$350M* (FY99 U.S.) including *$75 M* of contingency. Another ≈ *$850 M* would be required for auxiliary heating, startup diagnostics, power supplies and buildings to put the project at a new site.

Plasma Performance Projections

The physics issues and physics design guidelines for projecting burning plasma performance in FIRE are similar to those for ITER-FEAT. The operating regime for FIRE is well matched to the existing H-mode database and can access the density range from $0.3 < n/n_G < 1.0$ through a combination of pellet fueling and divertor pumping. This flexibility is important for investigating the onset of alpha-driven modes at the lower densities and to optimize the edge plasma for confinement studies and optimal divertor operation. The performance of FIRE [see Figs. 8 and 9] was projected by selecting JET data with parameters similar to FIRE, namely $\beta_N \geq 1.7$, $Z_{eff} < 2.0$, $\kappa > 1.7$ and $2.7 < q_{95} < 3.5$. The average *H(y, 2)* and density profile peaking, $n(0)/<n>_V$ for these data was found to be *1.1* and *1.2*, respectively. This is consistent with the analysis of JET H-mode data presented by Cordey et al [3].

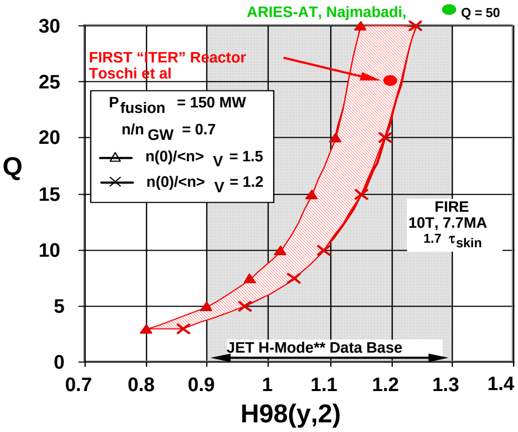

Fig. 8 Fusion gain for FIRE

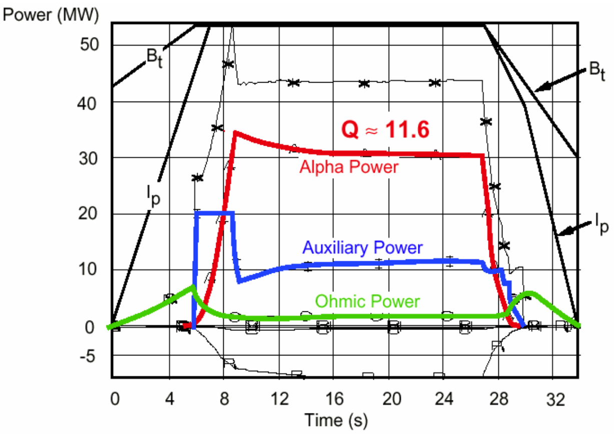

Fig. 9 Evolution of a burning plasma

A *0-D* power balance code was used to calculate the *Q*-value in FIRE as a function of *H*-factor as shown in Fig. 8. The density profile was assumed to have $n(0)/<n> = 1.2$ (X points) or *1.5* (Δ points) with *3%* Be and self-consistent alpha ash accumulation. On this basis, FIRE would be expected to achieve $Q \geq 10$ for JET-like H-modes. Physics based models using marginal stability transport models such as GLF23 also predict *Q* values in the range ≈ *10*. These models dependent sensitively on the value of the temperature of the H-mode pedestal, which is projected to be higher for plasmas with strong shaping (triangularity) and low pedestal density (relative to the Greenwald density). A next step experiment, such as FIRE, would provide a strong test of these models and improve their capability for predicting reactor plasma performance. A *1 1/2 -D* Tokamak Simulation Code (TSC) simulation of this regime with $H(y,2) = 1.1$ and $n(0)/<n> = 1.2$ indicates that FIRE can access the H-Mode and sustain alpha-dominated plasmas for $\tau_{pulse} > 20\ \tau_E, > 4\ \tau_H$ and $\sim 1.5\ \tau_{CR}$ as shown in Fig. 9. In addition, time is provided for plasma startup and a controlled shutdown to avoid plasma disruptions. The burn phase can study plasma profile evolution, alpha ash accumulation and techniques for burn control and begin studies of plasma current evolution due to alpha heating.

A longer term goal of FIRE is to explore advanced tokamak regimes using pellet injection and current ramps to create reversed shear plasmas (e.g., PEP modes), and then applying lower hybrid current drive to sustain the AT mode at high fusion gain $(Q > 5)$ for a duration of *1 to 3* current redistribution times. Simulations using TSC with self-consistent lower hybrid current drive modeling show that *100%* non-inductively driven burning plasmas could be sustained at $\beta_N \approx 3$, *64%* bootstrap current with $Q \approx 7.5$. A fusion power of *150 MW* would be achieved if confinement enhancements $H(y,2) \approx 1.6$ were attained at $B = 8.5T$ and $I = 5.5\ MA$. An important feature of the FIRE cryogenic copper alloy magnets is that the pulse length increases rapidly as the field is reduced with flattops of ~ *40 s* at *8 T* and ~ *90 s* at *6 T*. The primary limitation to exploiting this long pulse capability is the generic problem of handling the plasma exhaust power under reactor relevant conditions.

Assessment of FIRE (Advantages/Disadvantages)

FIRE does not seek to demonstrate that our existing knowledge is correct nor to avoid important physics issues. Rather the philosophy of FIRE is to explore the science of burning plasmas as fully as possible within the cost constraints of a $1B class laboratory. FIRE is a natural extension of the existing large tokamaks, and is based on the extensive international H-mode database for projecting performance to the burning plasma regime. Due to the high magnetic field, the extrapolation required to attain $Q \approx 10$ is a modest factor of *3* in terms of the normalized confinement time. While this reduces the uncertainty in attaining a burning plasma, it does not extend some plasma parameters (e.g., ρ^*) to full reactor values. The MHD stability characteristics of FIRE, with $q_{95} \approx 3.1$ *and* $\beta_N \approx 1.8$ for initial burning plasma experiments, are similar to the standard MHD regimes in existing tokamaks and will explore the synergistic effects of energetic alphas and MHD modes such as sawteeth and TAE modes. Operation at $\beta_N \approx 3$ or higher in later phases would begin to explore the important areas of neoclassical tearing modes (NTM) and resistive wall modes (RWM). Lower hybrid current drive and feedback stabilization would be evaluated as experimental tools to investigate the control of NTMs and RWMs. Divertor pumping and pellet fueling will allow FIRE to vary the density, and hence the TAE driving terms $R \nabla\beta_\alpha$, by a factor of three providing a good test bed for exploring the instability boundary for TAE modes and determining the transport of energetic alpha particles due to multiple overlapping TAE modes.

The double null divertor configuration produces the strongest plasma shaping that is critical for resolving and exploiting a number of physics effects related to confinement and MHD stability. The double null divertor may also significantly reduce the frequency and intensity of vertical displacement disruptions, which is a critical issue for the feasibility of a tokamak based reactor.

The disadvantage of this approach is the cost associated with the divertor and its impact on space inside the TF coil. The high power density in FIRE poses a significant challenge for the divertor and first wall designs, but this is a generic issue for magnetic fusion. The success of FIRE in this area would yield important benefits for technology development for future fusion devices.

A critical issue for all next step experiments is to supply auxiliary heating power at high power densities. FIRE proposes to use ICRF heating that has been demonstrated on existing experiments but the high power densities and neutron wall loading present in FIRE will require significant plasma technology R&D. This R&D will be needed if ICRF is to be used in any fusion application. The toroidal magnet flat top of *20 s* at *10 T* is sufficient $(\approx 20\tau_E, \approx 4\tau_{He})$ for a thorough investigation of burning plasma physics under conditions approaching steady-state, and would allow the initial investigation of advanced modes with significant bootstrap current fractions under quasi-stationary conditions $(1 - 2\ \tau_{CR})$ in a high gain burning plasma.

References

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ITER-FEAT, A One-Step to DEMO Advanced Tokamak Facility

Design Goals

During the 1980's, the success of experiments on tokamak devices in many nations pointed to a common physics basis and, in broad brush, to common parameters of an experimental burning plasma facility based on reactor-relevant superconducting coils. This motivated launching of the ITER Design Activities with the programmatic objective to "demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes." International cost sharing was also a goal.

The ITER-FEAT design is aimed at fulfilling this programmatic objective at minimum cost with a facility that is sufficiently flexible to investigate optimization of the tokamak concept in the Advanced Tokamak (AT) mode of operation. It will do this while additionally providing basic technological data regarding superconducting coils, high-heat-flux components, disruption-tolerant engineering solutions, as well as tritium breeding and high temperature cooling via test blanket modules. The design also makes use of discharge shaping in the poloidal plane to enhance confinement and β limits. The current ITER-FEAT design is sized to achieve $Q = 10$ with margin and to fulfill the programmatic objective with costs reduced relative to the 1998 FDR ignition design. Additional information regarding ITER-FEAT is available in the literature [1,2].

A key feature of the ITER-FEAT design is that it fulfills a one-step-to-DEMO requirement called for by the programmatic objective quoted above. This means that ITER-FEAT will be able to supply the necessary scientific and technological data to design a first demonstration fusion power reactor and to choose its operational mode, either inductive or steady state AT, based on direct experimental demonstration. The one-step-to-DEMO strategy minimizes the time and integrated cost required demonstrating the scientific and technological feasibility of fusion energy. Extrapolation of ITER-FEAT data to a demonstration reactor will be minimal.

While the U.S. participated in ITER design efforts during 1992-1998, the present ITER-FEAT design was carried out by a three-party collaboration composed of the European Union, Japan, and the Russian Federation. The physics specifications developed to fulfill the programmatic objectives are:

(1) To achieve extended burn in inductively driven plasmas with a ratio of fusion power to auxiliary heating power, Q, of at least 10 for a range of operating scenarios and with a duration sufficient to achieve stationary conditions on the time scales characteristic of plasma processes.

(2) To aim at demonstrating steady-state operation using noninductive current drive with the ratio of fusion power to input power for the current drive of at least 5.

In addition, under favorable conditions, it should be possible to explore controlled ignition and fusion power levels up to twice the nominal level.

Design Description

The major elements of the ITER-FEAT design flow from its dual science and technology goals while minimizing costs. Superconducting magnets are called for by reactor economics and are needed for demonstrations of steady-state operation. The magnet, divertor structure, and other key design technologies have benefited from approximately $800M of technology R&D carried out during the EDA phase. To optimize confinement and minimize size, the magnetic field strength is the maximum consistent with superconducting technology. Plasma size is minimized subject to confinement adequate to achieve $Q = 10$ and sufficient power flow through the separatrix to assure H-mode operation. Elongation, which improves confinement and β limits, is maximized subject to the power available for vertical instability control. A single-null divertor configuration permits long divertor legs to accommodate uncertainties in divertor physics of a reactor-scale device. Special plasma facing components have been developed to withstand $10\ MW/m^2$. Both power and particle handling have benefited from experimental progress in obtaining detached divertors. Experimental validation of divertor modeling codes (such as B2 - EIRENE) supports their use in a design mode. Core fueling by inside-launch pellets combined with D-T and impurity gas-puff injection control of the scrape-off layer should isolate the issues of core burn control from power handling and divertor detachment considerations.

Thus the ITER-FEAT design is an integrated result of a multi-dimensional tradeoff. The nominal parameters are found in Tables 2 and 3. Table 2 displays in parentheses the extra margin associated with operation at $q_{95} = 2.6$, which is supported by data from JET. Figure 10 portrays the poloidal cross-section view.

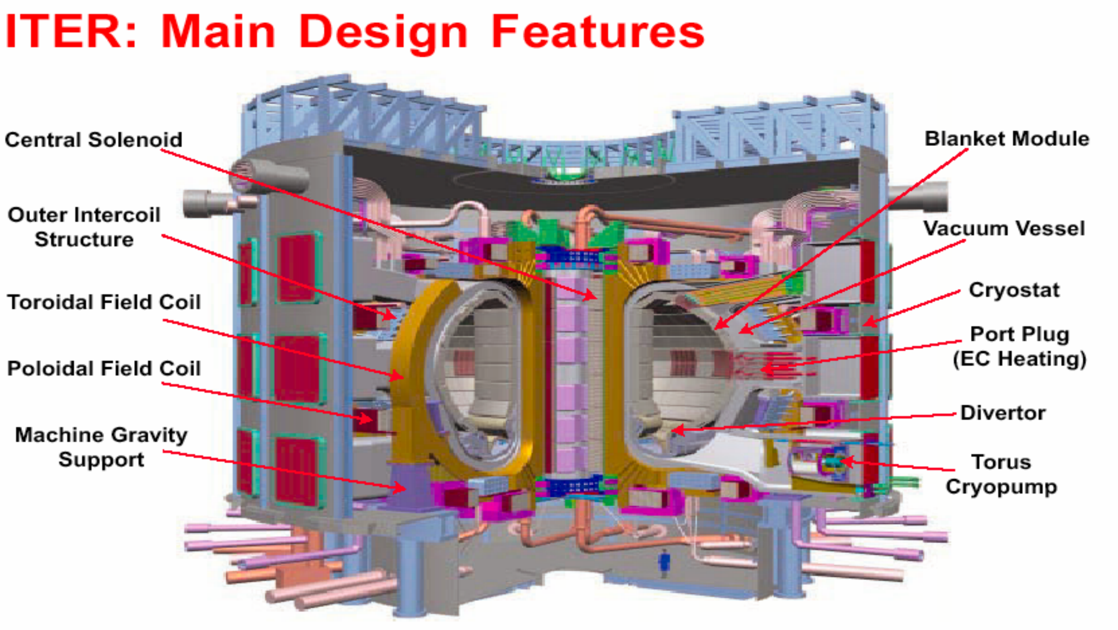

Figure 10 The Poloidal Cross-Section View of ITER-FEAT.

Operational Flexibility and Burning Plasma Science

Proponents note that the ITER-FEAT design supports a broad range of operational parameters, which can address both inductive and steady state advanced-tokamak issues. It has negative ion NBI heating that should also drive toroidal rotation. Toroidal velocity shear is essential to the stability of large-scale modes as well as to the triggering of transport barriers. Fast wave heating can produce either energetic minority particles or pure electron heating depending on experimental objectives. The presence or absence of energetic particles from auxiliary power systems will add considerable flexibility in the physics study of TAE modes. Electron cyclotron radiation sources will permit either heating or heating+current-drive operation. Moreover, as recent experiments show, Electron cyclotron current drive can stabilize neoclassical tearing modes, thereby removing their limit of $\beta_N \approx 2$ and permitting study of the processes associated with ideal MHD stability at $\beta_N > 3$ - almost twice the nominal β_N and, hence 3 times the nominal fusion power! ITER-FEAT differs from the FDR design in that it has a flexible poloidal field system with pancake central solenoid coils, which are required to generate highly shaped plasmas for advanced tokamak experiments. The nominal design point has $(\kappa_x, \delta_x) = (1.85, 0.49)$ and configurations with $(\kappa_x, \delta_x) = (2.0, 0.55)$ are accessible with a modest reduction in minor radius. The principal limitation on core shaping flexibility, as expressed by δ_x, comes from the requirement for long divertor legs and flexible divertor geometry. Error field correction coils also serve as actuators in magnetic feedback control of resistive wall modes. Clearly, the ITER-FEAT facility has the flexibility to optimize β for either inductive or advanced tokamak discharges. Power and particle handling facilities are also flexible and divertor chamber hardware can be readily exchanged. Pumping of the thermonuclear reaction product helium is assured. Melting and vaporization of divertor strike-plate material, as well as recovery hydrogen isotopes from co-deposited layers will be resolved in early hydrogen experiments.

Science Issues for Reactor-Scale Burning Plasmas

This report has described in some depth the new science issues anticipated in the burning plasma regime. For a complete, documented discussion of these issues, consult the ITER Physics Basis, Chapter 9 "Opportunities for reactor scale experimental physics [3]". Table 4 summarizes these issues and the capability of ITER-FEAT to address these issues.

Table 4. Representative Science Issues for Reactor-Scale Burning Plasmas

Issue	ITER-FEAT Capability.
Excitation of TAE Modes by fusion α-particles and by energetic particles created by auxiliary heating.	Uses α-particle and electron heating to attain reactor-level core density and temperatures and corresponding fusion α's. Has flexibility to create additional energetic particles by auxiliary heating.
TAE Mode Turbulence for high toroidal mode numbers.	Critical toroidal mode number n needed for instability is $n >> 1$ and scales inversely with normalized gyroradius.
Energetic particle and high conductivity effects on **(1,1) Modes.**	Flexible q-profile and energetic particle source for stabilization of (1,1) modes by fusion α-particles.
ELMy H-mode β_N limitations by Neoclassical Tearing Modes.	Demonstrates stabilization by ECCD for reactor-scale plasmas. Determines trigger process for a large, high-conductivity plasma.
Attaining Ideal β Limits via plasma shaping, rotation, error fields, and feedback stabilization of kinks.	Provides NBI or ICRF rotation drive needed to make the plasma rotate with respect to the wall, and thereby realize fixed boundary MHD limit. Correction coils feedback stabilize kinks and cancel error fields, reducing drag on rotation. Pancake central solenoid increases shaping flexibility.
β-Limits of *100%* Bootstrap Current AT discharges vs. κ, δ, rotation.	Determines minimum toroidal field needed to achieve steady-state operation of reactor-scale plasma with dominant ECH heating.
Thermal stability of coupled heat and poloidal flux diffusive transport for AT, very high bootstrap fraction, steady-state discharges. Optimization vs. κ, δ, n, etc.	Provides fusion and auxiliary power source to create *100%* bootstrap current, steady state plasmas. Superconducting coils permit burn durations exceeding *2000s*.
Control of Fusion Power by core density.	High-Q or ignition plasmas combined with inside-launch pellet capability to adjust core density.
Core Confinement Scaling for reactor-level values of ρ^*.	Provides ELMy H-Mode discharges with $1/\rho^*$ values a factor-of-*4* greater than present experiments.
Confinement Optimization versus κ, δ, ε, q-profile, and rotational shear	Flexible PF system. Auxiliary heating system drives rotation.

Marginal stability and core confinement profiles.	Provides intense, localized ECH heating source to measure profile response to changes in heat deposition profile.
H-mode power threshold and operational space.	Full flexibility for plasma shape, density, surface area, as well as high auxiliary power.
Density limit and profiles; collisional vs. collisionless core microturbulence.	Plasmas close to or exceeding the Greenwald value have a much lower collisionality in ITER compared to present devices.
Pedestal Physics and Plasma Boundary Conditions. Thermal, density, and toroidal rotation profiles in the core depend on boundary conditions at the top of the H-mode pedestal.	Scaling of pedestal values depends on pedestal width, which can vary with normalized gyroradius. Establishes effect of plasma shape on pedestal width.
Integrated core/edge physics and density control. Sufficient density for detached radiative divertor is less than core density needed for fusion power.	By inside pellet launch as well as by gas-puff sources of hydrogen isotopes and radiating impurity species, density is separately controlled on core and SOL sides of H-mode barrier.
ELM Energy Content and other Properties of Type I ELMs.	Pedestal height and width possibly depend on normalized gyroradius, which will be much smaller in reactor-scale plasmas.
Divertor Physics: Attachment, detachment, recombination, helium concentration and pumping.	Flexible divertor hardware retains long divertor legs; permits V-shaped divertor strike point regions, high pumping rates, isolation of divertor and main chamber SOL physics.
Reactor-scale Disruption Phenomenology; Demonstration of disruption tolerant engineering solutions.	Plasma energy content is sufficient to melt and vaporize divertor strike points, leading to impurities in the main plasma, ***JxB*** forces associated with induced and halo currents, and runaway electron currents.
Tritium recovery procedures.	Tritium is co-deposited with hydrogen isotopes, especially during disruptions & Type I ELMS.

Since the design of ITER-FEAT is complete, a decision to commence construction would have first plasma by 2010 and full *D-T* operation 6 years later. The credibility of fusion power will be established by fusion burns of at least 500 MW for 500 seconds and an operational mode demonstrated. By 2030, the design of a first demonstration reactor should be complete and fusion power will no longer be 40 years away, but at the threshold of commercialization.

Assessment (advantages/disadvantages)

Proponents Claim: The ITER-FEAT approach employs a single facility for the necessary integrated physics and technology investigations at a minimum integrated cost. Since tokamak science at the reactor scale differs from that of present devices, ITER-FEAT will provide the relevant science basis for fusion energy. It is truly remarkable that the device size needed for sufficient α-particle heating has also a power output in the range of a commercial power station, a wall neutron flux approaching materials limits, a size somewhat larger than the neutron shielding required for superconducting magnets, and requires a confining magnetic field pressure close to the limits which superconducting technology can provide.

ITER-FEAT is no higher risk than modular approaches because all the technological goals must be met in any event. ITER further provides for reactor-scale development of advanced and steady state burning plasma scenarios with as much flexibility as a tokamak can implement. It is the only next-step tokamak for which international collaboration on construction could be foreseen at the present time and leads to a commercial fusion power circa 2050. A large advantage is derived by international cost sharing. The nominal annual cost-per-party during the 8-year construction period is $150M.

Critics Claim: The ITER-FEAT facility total cost to all parties of $4.8B places it out of reach for an energy technology demonstration. Moreover, in spite of the technological readiness and the large generic contributions of a burning plasma experiment, the large leap to "one-step-to-Demo" of ITER-FEAT specializes to the tokamak concept too early in the development of fusion energy. One should wait for the possible development of an alternative approach before moving to reactor-scale research. Similarly, science carried out in present tokamak facilities may permit a more judicious and optimized choice of reactor configuration.

References

[1] D.J. Campbell, Phys. Plasmas **8**, 2041 (2001).
[2] Y. Shimomura, *et al,* Nuclear Fusion **41**, 309 (2001).
[3] ITER Physics Basis Editors, et al. Nuclear Fusion **39** 2627 (1999).

D. Justification for a New Burning Plasma Experiment

The scientific challenge of MFE research is to achieve a fusion burn wherein the energy released by the charged particle fusion products - the alpha particles - is the dominant heating source maintaining the plasma fuel temperature in order to produce high gain, net energy producing, sustained fusion reactions. Past research, for nearly 50 years, has been focused on achieving the necessary confinement conditions that would be needed to produce such self-heating. It is now believed that tokamak experiments can be designed that will fulfill the needed confinement conditions. A major scientific milestone will be achieved when fusion power is produced and reliably sustained in this manner.

However, achievement of this milestone opens up new, crucial, scientific issues that cannot be addressed in existing non-burning experiments alone. Simply put, these experiments, because of their limited scale, are just not capable of producing the necessary plasma performance in terms of the simultaneous achievement of the absolute plasma parameters needed to reach the burning plasma regime in addition to studying their nonlinear coupling. The definitive determination of how to overcome potential difficulties associated with having a significant partial pressure of energetic particles in the system - high β_α - requires a burning plasma experiment. Some reasons are as follows: energetic particles (alpha particles in a D-T plasma) (1) may produce additional instabilities that set boundaries to the regimes that a burning plasma can achieve, (2) alter MHD criteria that establish the limits on pressure (i.e. β) that plasmas can attain, (3) affect the evolution of critical plasma parameters, an evolution that may change substantially since the heating is no longer controlled by direct external means, (4) may effect edge power handling issues, particularly if a sudden loss of non-thermalized charged fusion products arises, (5) possibly alter transport scaling laws obtained in the absence of highly energetic particles, and (6) give rise to ash removal issues that now can only be partially addressed.

Thus a new burning plasma experiment will allow the completion of the cycle of research, in which a plasma experiment is performed that has sufficient confinement to produce net fusion energy, and in which new physics issues that can potentially alter physical properties throughout the plasma, can be studied. Such an experiment will be a major step towards demonstrating that magnetic fusion confinement offers a viable option to the world's long-term energy needs.

V. Findings of the Panel

On the basis of the two University Fusion Association Burning Plasma Workshops, the Snowmass Proceedings, numerous prior year studies of burning plasma physics, public comment at the 2001 Sherwood Meeting and the 2nd UFA BPS Workshop, and our own deliberations, the panel has arrived at the following set of findings:

A. Credibility of Fusion as an Energy Option

A burning plasma experiment is the crucial next step in establishing the credibility of magnetic fusion as a source of commercial electricity

B. The Next Scientific Frontier

The next frontier in the quest for magnetic fusion energy is the development of a basic understanding of plasma behavior in the regime of strong self-heating, the burning plasma regime.

C. Frontier Physics Issues in a Burning Plasma

Production of a strongly, self-heated fusion plasma will allow the study of a number of new phenomena depending on the degree of alpha self-heating achieved. These include:

- The effects of energetic, fusion-produced alpha particles on plasma stability and turbulence,
- The strong, non-linear coupling that will occur between fusion alpha particles, the pressure driven current, turbulent transport, MHD stability, and boundary-plasma behavior,
- Stability, control, and propagation of the fusion burn and fusion ignition transient phenomena.

D. Generic Issues in a Tokamak Burning Plasma Experiment

A burning plasma experiment in a tokamak configuration is relevant to other toroidal magnetic configurations. Much of the scientific understanding gained will be transferable. Generic issues include the effect of alpha particles on macroscopic stability and alpha particle losses, RF and neutral beam heating technology, the methods used to handle edge power losses, particle fueling and removal, and the feedback mechanisms needed to control the fusion burn. Equally important, the experience gained in burning plasma diagnostics, essential to obtaining data to advance fusion plasma science, will be highly applicable to burning plasmas in most other magnetic configurations.

D. Advancement of Fusion and Plasma Technology

The achievement of burning plasma conditions will lead to advances in fusion and plasma technology essential to operation of a reactor and in basic materials science. However, a number of important technological and material issues facing a fusion reactor will remain to be addressed.

F. The Need for a New Experiment

Present experiments cannot achieve the conditions necessary for a burning plasma. Therefore, addressing the important scientific issues in the burning plasma regime requires a new experimental facility.

G. Technical Readiness for a Burning Plasma Experiment

The tokamak configuration is scientifically and technically ready for a high gain burning plasma experiment. No other magnetic configuration is sufficiently advanced at this time.

I. Range of Burning Plasma Options

There exists a range of experimental approaches proposed to achieve burning plasma operation, from compact, high field, copper magnet devices to large super-conducting magnet devices. These vary widely in overall mission, schedule and cost.

J. Sufficient Information to Proceed to the Next Step

Sufficient scientific information is now in hand to determine the most suitable burning plasma experiment for the U.S. program.

K. Cost of a Burning Plasma Experiment

Approximate construction cost estimates of a burning plasma experiment range from hundreds of millions to several billion dollars. A burning plasma experiment, either a large scale international collaboration or smaller scale experiment solely within the U.S., will require substantial funding - likely costing the U.S. more than $100M per year.

L. Importance of the Base Program

A healthy base science and technology program is needed to advance essential scientific and technology issues and to capitalize on advances made with the burning plasma experiment. Thus, a burning plasma experiment must be funded with a significant augmentation of the fusion budget.

M. Desirability of Multiparty International Experiment

A multiparty international experiment has the potential of lowering the cost per party while retaining full technical benefits, representing a highly leveraged investment. However, the necessary political arrangements and multinational commitments can lead to delays and accumulated costs. In addition, the U.S. national scientific infrastructure benefits more from a burning plasma facility built in the United States.

N. Desirability of Advanced Tokamak Capability

Achieving burning plasma conditions does not require Advanced Tokamak (AT) capability. However, the AT line of research has the potential to significantly increase the economic attractiveness of the tokamak. Therefore, the AT capability is highly desirable.

O. Other Applications of Burning Plasmas

In addition to fusion energy production, there are a number of other potential fusion applications compatible with reduced plasma performance (such as transmutation of nuclear wastes and fusion-fission hybrid reactors) that would benefit from the knowledge gained in a burning plasma experiment.

P. U.S. Collaboration on JET

The JET experiment has the capability to explore alpha particle physics, at low gain, in regimes relevant to burning plasmas. The U.S. would benefit from collaboration on this experiment.

Q. Contributions to Other Fields of Science

The conceptual basis and analytic/computational techniques developed in magnetic fusion research have been productively transferred to space-, astro-, accelerator-, and computational physics. The new regimes accessed in a burning plasma experiment (*e.g.* reconnection in the presence of energetic particles and fusion burn dynamics) will extend these contributions.

VI. Recommendations

Based on this analysis the panel makes the following recommendations to FESAC.

A. Planning and Constructing a Burning Plasma Experiment

NOW **is the time for the U.S. Fusion Energy Sciences Program to take the steps leading to the expeditious construction of a burning plasma experiment.**

The critical burning plasma science issues have been recognized for nearly two decades. They have been investigated theoretically and in a limited way experimentally. Substantial scientific progress has been made by exploiting the capabilities of existing facilities. However, the U.S. Fusion Science Program now needs a new facility to move forward. Based on our progress to date, the community has in hand a knowledge base sufficient to design a burning plasma experiment and to move on to a new frontier of vigorous experimental fusion science, inaccessible to present machines. In addition to the strong scientific justification for a new facility there is additional motivation because of the public's increasing awareness of the importance of energy to the general well being of the nation and the fact that the solution involves a long-term investment in research.

B. Funding for a Burning Plasma Experiment

Funds for a burning plasma experiment should arise as an addition to the base fusion energy science budget.

A burning plasma experiment, either international or solely within the U.S., will require substantial funding - likely more than $100M per year. The largest part of this funding should be provided as an addition to the present fusion budget. It is crucial that funding for the project not be generated at the expense of maintaining a balanced base fusion science and technology program. The present program is positioned to develop key insights and develop new understanding into important unresolved science issues, which will ultimately lead to further improvements in the broad spectrum of magnetic fusion concepts. Premature termination of important components of the base science and technology portfolio would be shortsighted. In particular, it would reduce the discovery of important new plasma science phenomena and deplete the fusion science expertise that will be essential when the new facility comes on line.

C. The U.S. Plan

The U.S. Fusion Energy Sciences Program should establish a proactive U.S. plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs, the U.S. should be ready

to act and take advantage of it, but should not be dependent upon it. The U.S. should implement a plan as follows to proceed towards construction of a burning plasma experiment:

- Hold a "Snowmass" workshop in the summer 2002 for the critical examination of proposed burning plasma experiments and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the workshop has three purposes. First, while most of the MFE community has already agreed that we are technically ready to proceed with a burning plasma experiment, there must be a critical mass of fusion energy science community support that confirms that *the time to proceed is now* and not some undefined time in the future. Second, the community should carefully examine, on a scientific and technological basis, the viability of each of the burning plasma options presented, particularly ITER-FEAT, FIRE, and IGNITOR. The goal is for the proponents of each option to convince the community that their respective option is sufficiently well advanced that if built, it would have a high probability of success. Third, the community should agree that under the assumption that every member has had the opportunity to express his or her opinions in a pubic forum, the community as a whole will support whatever decision is ultimately made.

  At the workshop there is no need to have extensive discussions of "general" burning plasma science issues (these discussions have already taken place). Also, it should *not* be a goal of the workshop to select the "best" option, as this will likely not be possible and might lead to counterproductive polarization within the community. The emphasis should be on establishing the credibility of success of each design with respect to its stated scientific mission, cost estimate, and time schedule.

- The NSO should organize the preparation of a uniform technical assessment for each of the burning plasma options for presentation at the Snowmass summer workshop, which is described in Recommendation D. An NSO team of independent experts would carry out this work with support from the advocates of each option. Each NSO expert would be responsible for examining a given scientific area (e.g. MHD) across the board for all options. It is essential that the technical assessments be prepared in a uniform and self-consistent manner (e.g. using the same codes and methodology to test MHD stability, transport predictions, AT operation, etc.). This is essential in order that the credibility assigned to each option by the Snowmass community is determined fairly and consistently with respect to level of detail, rigor, and standards as compared to the other options. Although it is not the goal at Snowmass to choose it should, nevertheless, be possible for the community to compare each option on a fair basis.

- The Office of Energy Sciences should direct FESAC to form a high-level "action" panel in spring 2002 to chart the future U.S. course of action with respect to a burning plasma experiment. Many options are possible. Among the more obvious ones are: (1) building FIRE as a U.S. experiment with or without international collaboration, (2) building IGNITOR, either in the U.S. or Italy, in collaboration with the Italians, and (3) rejoining the ITER-FEAT project as a serious partner. The specific goal of the "action" panel is to select and carefully define a single, best path of action from among the various options. The panel will need to interact with DOE, Congress, OMB, and the international community in developing its choice since important political and financial issues must be considered in addition to the scientific and technological desirability of each option. The selected option should be communicated to the Director of the Office of Science by January 2003 to be consistent with submission of a report by DOE to Congress no later than July 2004 as proposed in the Fusion Energy Sciences Act of 2001.

- Initiate a review by a National Research Council panel in Spring 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by fall 2003. This is consistent with the submission of a report by DOE to congress no later than July 2004. The purpose of this step is to have the general non-fusion scientific and engineering communities assess whether (1) a burning plasma experiment is the logical next step in our program, (2) we are ready to proceed scientifically and technologically, and (3) we are recommending an attractive and viable option with strong and broad community support.

- Initiate an outreach effort coordinated by FESAC (or an ad-hoc body) to establish appreciation and support for a burning plasma experiment from science and energy policy makers, the broader scientific community, environmentalists and the general public. This effort is consistent with the general need, for example expressed by the NRC Panel, to convey the value of plasma and fusion science to the science community. This outreach effort should begin now.

A summary of the time schedule for the various components of the U.S. plan is given in the diagram at the end of the section.

D. The Next Step Option (NSO) Program

The NSO program should be expanded both financially and technically in order to organize the preparation of a uniform technical assessment for each of the burning plasma options, ITER-FEAT, IGNITOR, and FIRE, for presentation at the Snowmass summer study.

The NSO program is currently focused primarily on a pre-conceptual design of the FIRE experiment. This work should continue in order for the community to have the best information available when evaluating this option.

The mission, goals, science, engineering, cost, and time schedule for each option should be included in the technical assessments. This would require a major involvement of the existing, already funded, fusion community as well as the allocation of approximately \$1M - \$2M for new work required during the year. The assessments would be organized and led as part of the NSO program.

The development of the uniform technical assessments requires close interaction between the NSO program and the physics and engineering design teams for the burning plasma experiment options. This is straightforward for FIRE but will require special efforts with respect to interactions with IGNITOR and ITER-FEAT. In addition to the focused efforts of the NSO program it is essential that the U.S. fusion community at large be able to actively participate during the development of the technical assessments and not just act in a reviewing capacity at the Snowmass summer study.

For ITER-FEAT there is considerable information available to prepare the technical assessment. In fact, because of the huge effort already expended, the technical assessment has essentially already been made. Thus, the NSO activity will primarily be focused on organizing the material in a form appropriate for the Snowmass meeting. Even so, since some technical questions will invariably arise it is important for the preparation of the most accurate assessment possible that the NSO have access to, and be able to interact with scientists in the ITER-FEAT project.

Similarly, in the case of IGNITOR a considerable effort, mainly supported by Italy, has already been devoted to the project. This information, however, has not as yet been fully disseminated within the U.S. fusion community. Thus, much of the work of the NSO program will be devoted to assembling and preparing the assessment from the information already available. Here too the NSO must have access to, and be able to interact with our Italian colleagues in the IGNITOR project.

J. International Burning Plasma Experiments

The U.S. needs to engage the international community in some appropriate capacity with respect to ITER-FEAT and IGNITOR so that these experiments, along with FIRE, can be evaluated on a level playing field.

Whereas two of the burning plasma experiments that we have considered (ITER-FEAT and IGNITOR) are being pursued outside the U.S. without U.S. involvement we recommend that DOE: (1) engage the respective parties to facilitate the technical interaction in preparation for the U.S. to evaluate its optimum experimental approach to burning plasma experiments (leading to Snowmass 2002), (2) begin informal discussions on possible U.S. involvement in those efforts, and (3) establish the groundwork for productive collaborations amongst burning plasma efforts.

Recommended US Plan for Burning Plasmas