DOE/SC-0041

Fusion Energy Sciences Advisory Committee

Review of Burning Plasma Physics

September, 2001

U. S. Department of Energy
Office of Science

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Burning Plasma Physics

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INSTITUTE FOR FUSION STUDIES
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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 Hazeltine

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

Herbert L. Berk	U. Texas
Riccardo Betti	U. Rochester
Jill Dahlburg	NRL/GA
Jeffrey P. Freidberg (Chair)	MIT
E. Bickford Hooper	LLNL
Dale M. Meade	PPPL
Gerald Navratil	Columbia U.
William M. Nevins	LLNL
Masayuki Ono	PPPL
Francis W. Perkins	PPPL
Stewart C. Prager	U. Wisconsin
Kurt Schoenburg	LANL
Tony S. Taylor	GA
Nermin A. 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.