Report of the FESAC Panel on

A BURNING PLASMA PROGRAM STRATEGY TO ADVANCE FUSION ENERGY

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A BURNING PLASMA PROGRAM STRATEGY
TO ADVANCE FUSION ENERGY

EXECUTIVE SUMMARY

Fusion energy shows great promise to contribute to securing the energy future of humanity. The risk of conflicts arising from energy shortages and supply cutoffs, as well as the risk of severe environmental impacts from existing methods of energy production, are strong reasons to pursue fusion energy now.

The world effort to develop fusion energy is at the threshold of a new stage in its research: the investigation of burning plasmas. This investigation, at the frontier of the physics of complex systems, would be a huge step in establishing the potential of magnetic fusion energy to contribute to the world's energy security.

The defining feature of a burning plasma is that it is self-heated: the 100 million degree temperature of the plasma is maintained mainly by the heat generated by the fusion reactions themselves, as occurs in burning stars. The fusion-generated alpha particles produce new physical phenomena that are strongly coupled together as a nonlinear complex system. Understanding all elements of this system poses a major challenge to fundamental plasma physics. The technology needed to produce and control a burning plasma presents challenges in engineering science similarly essential to the development of fusion energy.

Experimental study of a burning plasma has long been a goal of the U.S. science-based fusion energy program. There is an overwhelming consensus among fusion scientists that we are now ready scientifically, and have the full technical capability, to embark on this step. The fusion community is prepared to construct a facility that will allow us to produce this new plasma state in the laboratory, uncover the new physics associated with the fusion burn, and develop and test new technology essential for fusion power.

Three options are presently under consideration as burning plasma experimental facilities: the international ITER project, the U.S.-based FIRE project, and the Italian IGNITOR project. All three are tokamaks, the most extensively studied magnetic configuration. The projects are at different stages of development, and have different mission scopes, time schedules, and costs. ITER is a power-plant scale facility with a comprehensive science and technology program. It has a well-developed engineering design and negotiations for construction are underway. U.S. participation in ITER would have substantial domestic benefits. FIRE is a smaller scale facility with a broad science program. It has an advanced pre-conceptual design. International participation in FIRE would provide substantial benefits. IGNITOR has a well-developed design and is moving forward in Italy. Its operation would provide valuable insight into burning plasma science, although it is not designed to be the sole burning plasma facility in the world.

Recognizing the opportunity before us, the Fusion Energy Sciences Advisory Committee was charged by the Department of Energy to "recommend a strategy for burning plasma experiments." A FESAC panel was convened for this purpose. The recommendations of the Panel are based, in large part, on an extensive scientific assessment of the three options by the 2002 fusion summer study, a two-week meeting of 280 fusion scientists, preceded by eight months of preparatory activity.

Given this background, the Panel has produced a strategy to enable the U.S. to proceed with this crucial next step in fusion energy science. The strategy was constructed with awareness that the burning plasma program is only one major component in a comprehensive development plan for fusion energy. A strong core science and technology program focused on fundamental understanding, confinement configuration optimization, and the development of plasma and fusion technologies is essential to the realization of fusion energy. The core program will also be essential to the successful guidance and exploitation of the burning plasma program, providing the necessary knowledge base and scientific work force.

The Panel recommendations are guided by the design options and considerations presented above and by two primary findings:

ITER and FIRE are each attractive options for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths.

Because additional steps are needed for the approval of construction of ITER or FIRE, a strategy that allows for the possibility of either burning plasma option is appropriate.

With this background, the Panel puts forth the following major strategy recommendations.

Since ITER is at an advanced stage, has the most comprehensive science and technology program, and is supported internationally, we should now seek to join the ITER negotiations with the aim of becoming a partner in the undertaking, with technical, programmatic and timing considerations as follows:

> ***The desired role is that the U.S. participates as a partner in the full range of activities, including full participation in the governance of the project and the program. We anticipate that this level of effort will likely require additional funding of approximately $100M/yr.***
>
> ***The minimum acceptable role for the U.S. is at a level of effort that would allow the U.S. to propose and implement science experiments, to make contributions to the activities during the construction phase of the device, and to have access to experimental and engineering data equal to that of all partners.***
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> ***The U.S. performs a cost analysis of U.S. participation and reviews the overall cost of the ITER project.***

> ***The Department of Energy concludes, by July, 2004, that ITER is highly likely to proceed to construction and terms have been negotiated that are acceptable to the U.S. Demonstrations of likelihood could include submission to the partner governments of an agreement on cost-sharing, selection of the site, and a plan for the ITER Legal Entity.***

Since FIRE is at an advanced pre-conceptual design stage, and offers a broad scientific program, we should proceed to a physics validation review, as planned, and be prepared to initiate a conceptual design by the time of the U.S. decision on participation in ITER construction.

If ITER negotiations succeed and the project moves forward under terms acceptable to the U.S., then the U.S. should participate. The FIRE activity should then be terminated.

If ITER does not move forward, then FIRE should be advanced as a U.S.-based burning plasma experiment with strong encouragement of international participation.

If IGNITOR is constructed in Italy, then the U.S. should collaborate in the program by research participation and contributions of related equipment, as it does with other major international facilities.

A strong core science and technology program is essential to the success of the burning plasma effort, as well as the overall development of fusion energy. Hence, this core program should be increased in parallel with the burning plasma initiative.

A burning plasma science program should be initiated by the OFES with additional funding in FY 04 sufficient to support this strategy.

I. THE GRAND CHALLENGE OF FUSION

Fusion energy shows great promise to contribute to securing the energy future of humanity. The risk of conflicts arising from energy shortages and supply cutoffs, as well as the risk of severe environmental impacts from existing methods of energy production, are among the reasons to pursue fusion energy now.

Fusion energy release involves reactions in a very hot gas – a plasma – in which two light atomic nuclei combine to form a heavier nucleus. Fusion is the vast energy source that powers the sun and the stars. The raw material for producing the fusion fuels, deuterium (a heavy form of hydrogen) and lithium (from which the fusion fuel tritium is produced), are abundantly available to all nations for thousands of years. Plasmas that are hotter than the core of the sun have been produced and confined by strong magnetic fields in the laboratory. The fusion plasmas in our largest experimental facilities have yielded more than 10 megawatts of fusion power for about 1 second. Dramatic advances have been made in recent years in the understanding and control of such plasmas. Thus the challenge before us now is to make fusion energy practical.

Developing fusion as a source of energy is an exciting scientific and technological grand challenge. The science that underlies this quest is at the frontier of the physics of complex systems and contributes to the description of some 99% of the visible universe. The progress made in all areas of fusion energy research in the past decade, and the growing realization that the world must take action now to meet our long-term energy needs have set the stage for accelerating the development of practical fusion energy. This is recognized in the U. S. National Energy Policy released last year: “Fusion – the energy source of the sun – has the long range potential to serve as an abundant and clean source of energy.”

I.A Burning Plasma Science

A burning plasma is a crucial and missing element in the world fusion program. The defining feature of a burning plasma is that it is sustained largely by the heat generated through its own internal fusion reactions. This is in contrast to previous experiments in which most of the heating was applied from outside the plasma. When these reactions occur in a fusion power system, energetic alpha particles (helium nuclei) and neutrons are generated. The alpha particles are confined by the magnetic field and slow down, transferring their energy to maintain the high temperature of the plasma. When fusion alpha heating dominates the plasma dynamics, important new scientific frontiers will be crossed. To create a burning plasma on Earth and systematically determine its properties will be an enormous step forward for fusion energy research. It will enable major advances in all of the key areas of plasma science and technology, and contribute to the demonstration of magnetic fusion as a source of practical energy.

While delivering the fusion-sustaining heat, the alpha particles also represent a new dynamic source of energy to change the plasma pressure profile. Such changes in the plasma structure and dynamics can increase the loss of heat and particles from the plasma, and consequently to a reduction in fusion power. Alternatively, these may lead to a further increase in temperature and fusion power production. Understanding and modifying these effects on heat and particle transport, the subject of “burn control,” are essential elements of power plant development.

Any magnetically confined burning plasma system must necessarily have a large value of the magnetic field multiplied by the system-size so that the energetic particles, produced by fusion reactions in the plasma, can be well confined. Ions gyrating around the magnetic field in such a system follow nearly circular "gyro-orbits," and the ratio of the system size to the gyro-radius will enter a new regime in such an experiment. This ratio is a key parameter governing plasma turbulence, and a burning plasma will also open up new science in plasma turbulence. Furthermore, the fusion alpha particles can drive Alfven waves (first discovered in an astrophysical context), and in a burning plasma system new wave structures are possible which were not accessible in previous experiments. The effect of populations of energetic particles on large-scale plasma instabilities, analogous to solar flares, also enters a regime of new physics. Finally, because of the very strong heat and particle fluxes emerging from a burning plasma, and the influence of escaping alpha particles on energy deposition on the surrounding walls, burning plasma research will extend regimes of plasma-boundary phenomena well beyond previous experience.

Each of these phenomena individually is at the forefront of high temperature plasma physics. But perhaps the most challenging scientific aspect of a burning plasma is the strong coupling between the phenomena. Research on burning plasmas will be at the forefront of the study of complex systems and nonlinear dynamics, building on recent advances in theory and simulation. Exploring the properties and dynamics of a burning plasma will be a fundamental and profoundly exciting scientific challenge, generating broad intellectual benefits. Beyond its tremendous value to the development of practical fusion energy, achieving this state of matter – a self-heated "star" in the laboratory –will be a magnificent scientific achievement.

A burning plasma experiment will also provide unique opportunities to advance the development of technologies and the engineering database for follow-on devices needed for commercial power production. Plasma facing components will be pressed to previously unexplored limits in heat flux and neutron fluence. A whole class of important technologies needed for heating and fueling plasmas, as well as for driving plasma current, and for remote maintenance of fusion systems will be brought up to the next level of development.

This exciting next step to explore burning plasmas is an essential element in the Fusion Energy Sciences Program whose mission is to "advance plasma science, fusion science and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source." The study of burning plasmas will be carried out as part of an overall program that must include advancing fundamental understanding of the underlying physics through theory and computational simulation, optimization of magnetic confinement configurations and development of low activation materials and fusion technologies.

I.B The Development Path to Fusion Energy

The development path to realize fusion power as a practical energy source from a toroidal magnetically confined plasma requires progress in three major areas in addition to the element of burning plasmas:

- *Fundamental understanding of the underlying science:* Dramatic advances have been made in the last decade both through more sophisticated plasma diagnostic

measurements and through the greatly enhanced computational power now available to researchers. These efforts are essential because ultimately only a well-understood and fully controlled plasma can function as a reliable fusion power source. In its recent review of the fusion energy sciences program, the NAS/NRC endorsed the high quality of the scientific research in fusion and particularly emphasized the critical importance of science in attaining the goal of practical fusion power.[1]
- *Optimization of the magnetic confinement configuration:* Because the configuration of the magnetic field confining the fusion plasma has important implications for the practical realization of fusion power, configuration optimization must be pursued in parallel with the study of a burning plasma in order to be prepared for the step to a practical demonstration power plant. These optimization studies are based on, and contribute to, the fundamental understanding of high temperature plasmas. The Secretary of Energy Advisory Board, in its recent review of the fusion energy sciences program, highlighted the importance of pursuing this scientific element to assure the practicality of fusion energy.[2]
- *Development of low-activation materials and fusion technologies:* It will be necessary to develop and qualify environmentally and economically attractive materials for fusion application. Testing of the major technologies required for fusion will be provided both through the burning plasma facility and through neutron source test facilities designed to provide additional data on materials and component reliability, availability and maintainability.

Pursuing these scientific elements implements the three policy goals for the restructured science-based fusion energy program defined by the fusion community and FESAC in 1996: (i) Advance plasma science in pursuit of national science and technology goals; (ii) Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and (iii) Pursue fusion energy science and technology as a partner in the international effort. Recent fusion program emphasis has been on making progress in the first two of these scientific elements. However, the dramatic progress made in fusion energy research in the past decade, and the growing realization that the world must take action now to meet our long-term energy needs, has set the stage for initiating the study of the crucial and now missing element of burning plasmas in the development of practical fusion energy.

II. BACKGROUND

The necessity for a burning plasma program has been recognized for many years, and called for by the FESAC restructured Fusion Energy Sciences program of 1996. The recent resurgence of interest in moving forward with the study of burning plasmas was manifest by the initiation in 2000 of a series of burning plasma workshops sponsored by the University Fusion Association, involving fusion scientists from national laboratories, industry and universities.

Following these workshops, a FESAC panel was convened in 2000 to review burning plasma physics and to recommend a direction for studies underway assessing next step options.[3] Among its recommendations, that panel concluded that NOW is the time for the U.S. to take the steps leading to construction of a burning plasma experiment, that the funding for the experiment should be an addition to the core fusion energy science budget, and that the U.S. should establish a proactive plan on burning plasma experiments (and 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).

The FESAC panel also recommended three steps for the fusion community to bring the U.S. fusion program toward formulating a strategy for burning plasmas. First, a uniform technical assessment should be performed of the three present experimental options: IGNITOR, FIRE, and ITER. Second, a "Snowmass-style" workshop should be held in summer, 2002, in which the community assesses the scientific and technical viability of each of the three options, and affirms (or denies) the proposition that the time to proceed with a burning plasma experiment is now, not some undefined time in the future. Third, a FESAC "action" panel should be convened to chart the future U.S. course of action with respect to a burning plasma experiment. The first two activities have been completed. The 2002 Fusion Summer Study held in Snowmass, CO, completed the uniform technical assessment and demonstrated essentially unanimous and enthusiastic endorsement of the proposition that the fusion research community is ready, and now is the time, for this next step in fusion energy science research.[4]

The conclusions of the 2002 Fusion Summer Study were based on analysis led by over 60 conveners working with hundreds of members of the fusion energy sciences community extending over 8 months. This effort culminated in two weeks of intense discussion by over 250 US and 30 foreign fusion physicists and engineers covering all avenues of fusion energy research. The 2002 Fusion Summer Study assessment forms the scientific basis that has enabled the Panel to recommend a strategy. The present FESAC panel serves the role of the "action" panel. The conclusions and recommendations presented in Section IV are consistent with the earlier results of the FESAC Review of Burning Plasma Physics and with the 2002 Fusion Summer Study results.

The purpose of the 2002 Fusion Summer Study was to assess the options for the exploration of burning plasmas. The Study was not intended to, and did not, devise the best path or strategy to pursue these burning plasma options. That is the goal of the present FESAC panel.

The charge to the present panel is "to recommend a strategy for burning plasma experiments" (the full charge letter is contained in Appendix D). In developing the strategy we have considered carefully all three burning plasma options investigated at the 2002 Fusion Summer Study, making extensive use of the conclusions and findings of that Study.

As the US has evolved in its assessment of next step burning plasma options, significant activity has been underway simultaneously in the international fusion energy research program. In particular, the ITER burning plasma option has been moving forward with negotiations for possible construction by four partners: Canada, the European Union, Japan, and Russia. The engineering design of a reduced-size ITER device has been completed, four potential sites have been identified, and a schedule has been laid out that would lead to site selection and completion of negotiations in the near-term. The engineering design of IGNITOR, which is moving forward in Italy, is also complete. Finally, with the completion of an advanced pre-conceptual design of the

U.S.-based FIRE burning plasma experiment, information is in hand for the formulation of a decisive strategy.

Since its inception, fusion energy science research has been a paradigm for international collaboration. Throughout its history, fusion research has been a strongly interacting, closely-knit international program. In implementing the third policy goal of the Fusion Energy Sciences Program (to…pursue fusion energy science and technology as a partner in the international effort), this will surely be a key property of any burning plasma science program.

III. EXPERIMENTAL OPTIONS

Over the past year, the US community conducted a uniform technical assessment (here referred to as the Study) of three approaches, IGNITOR, FIRE, and ITER, that have been proposed to investigate burning plasmas. The Study identified the key scientific and technological burning plasma issues and opportunities and made assessments of the abilities of the three approaches to address them. As the Study's work has guided the predominant views of our panel, we present below a summary of their report.

III.A Mission Statement by Proposers:

The following mission statements were adapted from statements provided by the proposing teams to the Study.

- IGNITOR is a facility whose mission is to achieve fusion ignition conditions in deuterium-tritium plasmas for a duration that exceeds the intrinsic plasma physics time scales. It utilizes high-field copper magnets to achieve a self-heated plasma for pulse lengths comparable to the plasma current redistribution time. IGNITOR will study the physics of the ignition process and alpha particle confinement as well as the heating and control of a plasma subject to thermonuclear instability.
- FIRE is a facility whose mission is to attain, explore, understand and optimize magnetically confined fusion-dominated plasmas. FIRE would study burning plasma physics in conventional regimes with Q (the ratio of fusion energy output power to the externally applied power heating the plasma) of about ten and high-beta advanced tokamak regimes with Q of about five under quasi-stationary conditions. FIRE employs a plasma configuration with strong plasma shaping, double-null poloidal divertors, reactor level plasma exhaust power densities and pulsed cryogenically cooled copper coils as a reduced cost approach to achieve this mission.
- The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy. ITER would accomplish this objective by demonstrating extended burn of deuterium-tritium plasmas with Q at least ten, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of high heat flux and nuclear components required to utilize fusion energy for practical purposes. ITER also aims at producing nearly steady-state plasma regimes with

Q greater than five, and the possibility to demonstrate controlled ignition defined as Q of about thirty.

III.B Scope of Projects

1. Points in Common

The Study concluded that each approach would enable the investigation of the physics of burning plasma, advance fusion technology, and contribute to the development of fusion energy. IGNITOR, FIRE, and ITER would each make significant contributions to burning plasma physics and technology.

- Physics scope would include strongly-coupled physics issues of equilibrium, stability, transport, wave-particle interactions, fast ion physics, and boundary physics in the regime of dominant self-heating.
- Technology scopes would include (a) plasma support technologies (heating, fuel delivery, exhaust, plasma-facing components, and magnets) at parameters and plasma conditions close to those required for power production, and (b) nuclear technologies (remote handling, vacuum vessel, blankets, safety and materials) gained as a result of the experience of operating in a nuclear environment. The levels of technological benefit from the approaches will depend on tritium inventory, pulse length, duty factor, and lifetime fluence.

2. Differences in Opportunity

While all three approaches would make significant scientific and technological contributions in these physics and technology areas, the opportunities offered by the approaches are quite different. The Study clarified the following distinctions between the opportunities:

- IGNITOR offers an opportunity for the early study of burning plasmas aiming at ignition for about one plasma current redistribution period.
- FIRE offers an opportunity for the study of burning plasma physics in conventional configurations for a few plasma current redistribution time periods and in advanced tokamak configurations under quasi-stationary conditions (several plasma current redistribution time periods), and would contribute to plasma technology.
- ITER offers an opportunity for the study of burning plasma physics in conventional configurations for a few plasma current redistribution time periods and in advanced tokamak configurations for long durations (many current redistribution time periods) with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology.

3. Range of Studies

The benefits of the specific proposal beyond the ones common to all three approaches are:

- IGNITOR would especially study two physics topics: (a) the science of self-heated plasmas in a power plant relevant regime of small ρ^* (the ratio of the ion gyro-radius to the plasma's minor radius) for globally magnetohydromagnetic (MHD) stable plasmas at low β_N (normalized ratio of plasma pressure to magnetic field pressure), and (b) sawtooth stability at low beta with isotropic alpha particles and self-consistent pressure profile determined by dominant alpha heating. Technology scopes would include development of (a) high-field copper magnets with advanced structural features, and (b) high-frequency RF antennas for wave heating in a burning plasma environment.
- FIRE would especially address three physics areas: (a) the science of self-heated plasmas in power plant relevant regimes of small ρ^* and high β_N with a large fraction of non-inductively driven current sustained for up to a few plasma current relaxation times, (b) exploration of high self-driven plasma current regimes with strong shaping and active MHD stability control, and (c) study of removal of helium ash and impurities with exhaust pumping. Technological scopes would include development of (a) electrical insulation for high-field pulsed copper magnets in a high neutron fluence environment, and (b) high heat flux plasma-facing components with such materials as tungsten and beryllium that will have steady-state heat removal capability.
- ITER would especially address four physics areas: (a) the science of self-heated plasmas in power plant relevant regimes of small ρ^* and high β_N, and with the capability of full non-inductive plasma current drive sustained in near steady state conditions, (b) exploration of high self-driven plasma current regimes with a flexible array of heating, current drive, and rotational drive systems, (c) exploration of alpha particle-driven instabilities in a power-plant-relevant range of temperatures, and (d) temperature control and removal of helium ash and impurities with strong exhaust pumping. Technology scopes would include (a) integration of steady-state power plant relevant fusion technology: large-scale high-field superconducting magnets; long-pulse high-heat-load plasma-facing components; control systems; heating systems, and (b) testing of blanket modules for breeding tritium.

III.C Performance Projections

Based on an extensive experimental database, the Study applied the present understanding of tokamak physics to predict the ranges of performance of the three approaches. It concluded that there is confidence that ITER and FIRE will achieve the needed burning plasma performance in H-mode operation and that IGNITOR would achieve similar performance if it obtains enhancement of confinement by either achieving H-mode operation or by confinement improvement in tokamak L-mode operation. However, the likelihood of achieving these enhancements remains an unresolved issue between the assessors and the IGNITOR team.

Present uncertainties in transport models lead to some variations in the projected performance, particularly the fusion power gain. The Study also identified other outstanding scientific and technical issues relating to each of the three options. Most of these can be addressed through continuing research and development, including modeling and experiments on existing devices, in parallel with construction of a burning plasma experiment.

III.D Schedules and Costs

Construction schedules were reported as 5 years for IGNITOR, 6 years for FIRE, and 9 years for ITER. FIRE is not at the same level of readiness as ITER and IGNITOR and will require some additional time to be ready for construction. ITER must complete international negotiations and agreement before construction can commence.

Cost information was obtained from the ITER and FIRE teams and was assessed within the limited resources available. All costs were converted to 2002-US dollars. ITER assumes an international cost-sharing approach while FIRE costs are estimated as a US project.

- As an Italian project, IGNITOR has been designed in detail with supporting R&D. It has a detailed cost estimate that is confidential for business purposes and was not made available.
- The estimate for FIRE is about $1.2 B including about a 25% contingency. It is based on an advanced pre-conceptual design using in-house and some vendor estimates.
- The purpose of the ITER cost information is to provide accurate estimates of the relative "value" of all the tasks necessary for construction to facilitate international negotiations on task sharing. The cost information is based on a large engineering effort (about 1000 PPY) and a large R&D effort (about $900M) with prototypes of all key components. Also, the ITER cost information (about 85 procurement packages) is based on input from industries in all the present parties. The Study reports that the estimate of the ITER total "value," when converted to 2002 US dollars, is about $5 billion. The actual cost estimate is to be developed by each party using its own procedures, including the use of contingency. Thus, the ITER cost information does not included explicit contingency. In the recommended strategy (Section IV) the Panel estimates that the desired role for US participation in ITER will likely require additional funding of approximately $100M/yr. This cost is estimated for that of a non-host partner, for which the total cost to construction is anticipated to be approximately 20% of the ITER total value of $5B. If the cost is spread over ten years, the annual estimated cost is $100M.

The Study's engineering assessment concluded that there are no outstanding engineering-feasibility issues to prevent the successful design and fabrication of any of the three options. However, the three options are at very different stages of engineering development.

- ITER and IGNITOR have well-developed engineering designs:
- IGNITOR has carried out R&D and built full-size prototypes for essentially all major components.
- ITER has been supported by a comprehensive R&D program. Also, ITER has

demonstrated full-scale prototypes for essentially all major components of the fusion core and their maintenance.

- FIRE is at the advanced pre-conceptual design level. It has benefited from the R&D for CIT and BPX (previously proposed high magnetic field burning plasma projects), from the R&D that has supported the high magnetic field IGNITOR project, and most recently from the R&D of the ITER project.

III.E Paths for Future Development

Finally, we restate a portion of the Study conclusions on the roles of the three approaches within the development paths for fusion energy.

- IGNITOR allows early demonstration of an important fusion milestone, burning plasmas with a low initial facility investment cost. Because of its short pulse length, IGNITOR cannot thoroughly investigate burn control and/or advanced tokamak modes. IGNITOR could be an element of a portfolio of experiments supporting ITER-based or FIRE-based development scenarios.
- A FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions. This option aims at smaller extrapolations in physics and technology. Assuming a successful outcome, a FIRE-based development path provides for additional optimization before further integration steps are needed, allowing a more advanced and/or less costly integration step that will follow.
- An international tokamak research program centered around ITER, which includes other performance-extension devices throughout the world, has the highest chance of success in exploring burning plasma physics in steady-state. ITER will provide valuable data on integration of power-plant relevant plasma support technologies. Assuming a successful outcome (demonstration of high-performance AT burning plasma), an ITER-based development path would lead to the shortest development time to a demonstration power plant.

See Appendix B for the development path considerations of the Panel.

IV. THE RECOMMENDED STRATEGY

This section recommends a strategy to establish a U.S. burning plasma program. The scientific challenge of a burning plasma program, and its crucial role in the development of fusion energy, was discussed in Section I. An extensive and in-depth process carried out by the fusion energy science community has evaluated the detailed technical foundation for the strategy, as described in Section II. The powerful scientific opportunities offered by the three options for a burning plasma experiment are delineated in Section III. These three sections together establish the framework for our recommended strategy.

IV.A Basis for the Strategy

The recommended strategy follows from the following set of findings that derive from a scientific analysis of the experimental options and of the overall fusion energy development needs.

A burning plasma program is needed as a crucial scientific element in the development of fusion energy. The U.S. and world fusion programs are now technically ready to proceed with the construction of a burning plasma experimental facility.

The frontier science introduced by burning plasmas, the physics and technological challenge of creating this plasma state in the laboratory, and the importance of demonstrating the achievement of fusion power have long been appreciated. There is now essential unanimity in the fusion science community that we have the scientific and technological capability to accomplish these major steps.

A burning plasma experiment would be an integral part of the fusion energy sciences research program. Underpinning this program is a strong core science and technology element that will greatly benefit from, and contribute to, the burning plasma experiment.

The burning plasma effort was called for in the science-based fusion energy program restructured in 1996 and has been a missing element in our fusion energy sciences program. In addition to burning plasma science, the development path to fusion power requires fundamental understanding of the underlying science and technology, optimization of the magnetic configuration, investigation of steady-state plasmas, and the development of low-activation materials and fusion technology. A core science and technology program focuses on fundamental understanding, confinement configuration optimization, and the development of plasma and fusion technologies. These topics are advanced in the core program through experimental, theoretical, and computational activities. This core program is essential to the successful and full exploitation of a burning plasma program. The guidance of the burning plasma program rests on the knowledge and the scientific work force generated by the core program. The current level of effort within the core program, following the major budget reduction in 1996, is insufficient to meet these challenges.

The ITER facility is proposed as an international project at power-plant scale with a comprehensive science and technology program. It has a well-developed engineering design, and negotiations for construction are underway. U.S. participation in ITER would have substantial domestic benefits.

ITER offers the opportunity to investigate the strongly coupled, nonlinear physics phenomena that dominate self-heated plasmas, in near steady-state conditions at the size and scale expected for a power source. It has been designed by an international team, drawing on scientific and engineering talent from around the world. An extensive array of experimental tools will be available to control the plasmas and uncover the underlying science. Operation of the long pulse burning plasma will also advance our capabilities in a wide array of technologies needed for fusion energy development. The operation and study of a power-plant scale facility that integrates burning plasmas, near steady-state, and key fusion technologies would constitute a huge step toward commercial fusion power.

The FIRE facility is proposed as a smaller scale, U.S.-based project with a broad science program. It has an advanced pre-conceptual design. Conceptual and engineering designs are needed prior to construction. International participation in FIRE would provide substantial benefits.

FIRE offers the opportunity to investigate the strongly coupled physics phenomena that dominate self-heated plasmas, under quasi-stationary conditions. It has been designed by the U.S. Significant experimental tools will be available to control the plasmas and uncover the underlying science. Operation of a burning plasma in FIRE would advance specific plasma technologies relevant to fusion energy development. The burning plasma science learned would constitute a large step forward in fusion energy development.

IGNITOR has a well-developed design and is moving forward in Italy. Its operation would provide valuable insight into burning plasma science, although it is not designed to be the sole burning plasma facility in the world.

IGNITOR offers the opportunity for an early study of the strongly coupled physics phenomena that dominate self-heated plasmas. It is aimed at an early investigation of burning plasmas, and is enabled by a smaller size and less extensive technical capability.

ITER and FIRE are each attractive options for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths.

Both ITER and FIRE would uncover critical new science in, and generate a large leap in our understanding of burning plasmas, although there are differences in experimental capabilities. Viable and aggressive development paths have been formulated in which either ITER or FIRE form the primary and first burning plasma experiment. In either case, additional key elements are needed, although there are differences between the case in which integration of burning plasma physics, long pulse, and technology occurs earlier (ITER) and that in which it occurs later (FIRE). Both could contribute to, and benefit from, an interaction with the core science program, which aims to develop predictive capability and to extend the results to other magnetic configurations and new experiments.

Because additional steps are needed for the approval of construction of ITER or FIRE, a strategy that allows for the possibility of either burning plasma option is appropriate.

IV.B Major Recommendations

Since ITER is at an advanced stage, has the most comprehensive science and technology program, and is supported internationally, we should now seek to join

the ITER negotiations with the aim of becoming a partner in the undertaking, with technical, programmatic and timing considerations as follows:

> ***The desired role is that the U.S. participate as a partner in the full range of activities, including full participation in the governance of the project and the program. We anticipate that this level of effort will likely require additional funding of approximately $100M/yr.***
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> ***The minimum acceptable role for the U.S. is at a level of effort that would allow the U.S. to propose and implement science experiments, to make contributions to the activities during the construction phase of the device, and to have access to experimental and engineering data equal to that of all partners.***
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>
> ***The Department of Energy concludes, by July, 2004, that ITER is highly likely to proceed to construction with terms acceptable to the U.S. Demonstrations of likelihood could include submission to the partner governments of an agreement on cost-sharing, selection of the site, and a plan for the ITER Legal Entity.***

Since FIRE is at an advanced pre-conceptual design stage, and offers a broad scientific program, we should proceed to a physics validation review, as planned, and be prepared to initiate a conceptual design by the time of the U.S. decision on participation in ITER construction.

If ITER negotiations succeed and the project moves forward under terms acceptable to the U.S., then the U.S. should participate. The FIRE activity should then be terminated.

If ITER does not move forward, then FIRE should be advanced as a U.S.-based burning plasma experiment with strong encouragement of international participation.

If IGNITOR is constructed in Italy, then the U.S. should collaborate in the program by research participation and contributions of related equipment, as it does with other major international facilities.

A strong core science and technology program is essential to the success of the burning plasma effort, as well as the overall development of fusion energy. Hence, this core program should be increased in parallel with the burning plasma science initiative.

A burning plasma science program should be initiated by the OFES with additional funding in FY 04 sufficient to support this strategy.

V. PRIORITIZED OBJECTIVES FOR U.S. PARTICIPATION IN ITER

Achievement of the U.S. burning plasma goals requires that the implementation of the recommended strategy be guided by clear prioritized objectives, as detailed in Appendix C. U.S. negotiations regarding the ITER construction project and research program should assure that the U.S. participants will be able to achieve the highest priority objectives.

In prioritized order, U.S. objectives for U.S. participation in ITER are:

(1) to perform research on burning plasmas in the tokamak configuration, to contribute to the science base for the full range of toroidal confinement configurations;

(2) to develop enabling technology that supports the burning plasma research and positions the U.S. to more effectively pursue burning plasma research;

(3) to advance fusion energy technologies, to contribute to the technology base necessary for a demonstration fusion power plant; and

(4) to increase involvement of U.S. industry in the fusion program, both in design and fabrication of components for burning plasma experiments and in preparation for U.S. design and construction of a demonstration fusion power plant.

Achievement of the highest priority U.S. objectives requires that negotiated terms assure the following minimum roles and opportunities:

(a) a significant U.S. role in the decision-making regarding the ITER research program, including overall research directions and selection of experiments;

(b) opportunities for U.S. researchers from all segments of the U.S. fusion community (universities, laboratories, and industry) to propose, plan, conduct and participate in experiments as members of the ITER research team;

(c) opportunities for U.S. researchers to play leadership roles and participate in ITER's topical task forces, with access to all data from all available systems for all ITER experiments;

(d) opportunities to apply theory and integrated modeling in design and analysis of experiments and in benchmarking of models against ITER data;

(e) opportunities for the U.S. to develop and contribute equipment during the construction and operations phases of the device, and to have access to engineering data equal to that of all partners;

(f) opportunities to propose/develop/design/fabricate/install/operate advanced diagnostics and enabling technology (e.g., plasma control tools) beyond the baseline;

(g) opportunities to participate in fusion energy technology activities such as the development and testing of blanket modules.

References

1.*An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*, National Research Council, National Academy Press, 2001.

2. *Realizing the Promise of Fusion Energy*, Secretary of Energy Advisory Board Task Force on Fusion Energy, U.S. Department of Energy, August, 1999.

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APPENDICES

A. FUSION PROGRAM INTEGRATION

The Fusion Energy Sciences Program is developing the science and technology needed for an economically and environmentally attractive fusion power source. This includes three mission elements: the advancement of plasma science, the development of fusion science, technology and plasma confinement innovations through a portfolio approach, and the pursuit of burning plasma physics and fusion energy development as a partner in the international effort. As described earlier, this panel report recommends a strategy for initiating the crucial and now missing program element: the study of burning plasmas in the development of practical fusion energy. This Appendix describes the integration of this new burning plasma program into the overall Fusion Energy Sciences Program and into broader scientific, educational, and industrial contexts.

A.1 The Role of a Strong Program in Core Fusion Science and Technology

Recommendation 6 from the Snowmass Executive Summary states an essential feature of fusion program integration:

> A strong base science and technology program is needed to advance essential fusion science and technology and to participate effectively in, and to benefit from, the burning plasma effort. In particular, the development path for innovative confinement configurations would benefit from research on a tokamak-based burning plasma experiment.

We strongly endorse this recommendation. The base, or core, program develops underlying fusion science and technology and provides the knowledge base to optimize the magnetic configuration for plasma confinement. Thus, while the tokamak is presently in the most advanced stage of development and is presently the only configuration with the requisite data base required for extrapolation to the burning plasma regime, other configurations may be more desirable for ultimate deployment as power sources. It is therefore of critical importance that the exploration of these alternative magnetic configurations move forward expeditiously so that the understanding of their confinement properties reaches maturity prior to future decisions on the construction of a fusion demonstration facility. The burning plasma experiment based on the tokamak configuration will enhance this effort by providing generic scientific results and technologies, which can be incorporated into the knowledge base of these alternative approaches.

The core program is also essential to the successful and full exploitation of the burning plasma program. Predictions on the confinement, stability properties and dynamics of plasmas in the burning regime have all come from the intense experimental, modeling and theoretical efforts of the core program. The underpinnings of any burning plasma experiment therefore fundamentally rests on the foundation of knowledge that has come from the core program. Moving forward with a burning plasma experiment requires experimental scientists, engineers, and theorists and computational scientists from this core to design experiments and interpret the results.

A.2 Burning Plasma Studies Within the Overall Fusion Energy Sciences Program

The creation and control of a magnetically confined burning plasma is a scientific and technological grand challenge. Essential science and technology that is still being developed by the core fusion research programs of the world include understanding energy confinement and its scaling with system size, geometry, and magnetic configuration; demonstrating plasma heating techniques in the form of high energy neutral beams and radio frequency waves; and developing innovative technologies to handle the high heat flux at the edge of a burning plasma. The body of knowledge developed thus far has created confidence in designs for burning plasma experiments. The flexibility built into these designs will accommodate the inevitable uncertainties and challenges associated with a major research and development step.

Scientific flexibility, excellent diagnostics, and close coupling to theory and simulation are critical features of an integrated research program in burning plasma physics and technology. The understanding gained through the study of burning plasmas, when coupled with parallel advances in theory and simulation, will lead to more rapid progress towards the ultimate goal of an optimized fusion reactor concept. Moreover, because of the common principles underlying the physics of toroidal magnetic configurations, the time to implement and evaluate other promising approaches to magnetic confinement of high-temperature plasma may be reduced as a result of an integrated burning plasma development path.

While tremendous progress has been made, further developments are needed to exploit fully the benefits of the burning plasma program. Research on existing facilities enables improved predictions of the phenomena to be explored in burning plasma experiments, readies scientific instruments for fusion’s neutron environment, and addresses remaining technology issues. The physics basis for a tokamak burning plasma experiment will benefit from further understanding of such critical issues as the structure of the edge pedestal, the H-mode transition threshold, and the dynamics and stabilization techniques for “neoclassical tearing modes.” Technology research and development will improve plasma-facing materials for walls and divertor plates and address tritium retention issues. The ongoing exploration of these and other issues will play a critical role in ensuring the success of a burning plasma experiment in terms of science and technology output.

A.3 Strengthening the Core Science and Technology Program

To fully realize the investment in a burning plasma effort and to move towards the practical use of fusion energy, the core science and technology program should be strengthened. Examples of the strengthened core program that directly benefit the burning plasma program include novel diagnostic development and deployment, increased theory and computational efforts, optimized utilization of existing experimental facilities and enhanced technology development. Success in reaching our nation’s fusion energy goals will require expansion of the infrastructure of skilled and expert persons working on fusion. A strengthened core program will help meet this need, especially by training young scientific and engineering talents who share the vision of virtually unlimited energy for mankind and the intense curiosity over the underlying science.

Many of the benefits derived from a strengthened core program can be realized in the near term and applied during the early stages of a burning plasma program. Existing experimental facilities can develop and test the new instrumentation and plasma control capabilities needed to characterize and manipulate the high-temperature plasma dynamics in the burning plasma experiment. This in turn, when combined with the enhanced theory/computational effort and the increased facility utilization, would allow for (i) the development of more realistic and better validated models of burning plasma discharges and (ii) the development of improved plasma control strategies. Similar advances are expected from developments in technology. Strengthening of all of these activities increases the likelihood of discoveries that can be incorporated into a burning plasma experiment to enhance its performance.

A.4 The Impact of Burning Plasma Studies on Science and Technology Beyond Fusion

Research in a well-diagnosed and flexible burning plasma experiment will have impacts beyond the sphere of fusion science. Plasma pressure profile dynamics in the presence of intense alpha particle heating is a central component of burning plasma science. The associated study and controlled manipulations in the laboratory of matter under these extreme conditions will provide new challenges and insights and contribute to the broad scientific knowledge base of humanity. A deeper understanding of nonlinear dynamics and non-equilibrium statistical mechanics and transport will extend beyond fusion, as these disciplines are important to a diverse range of phenomena including fluid dynamics, chemical systems, biology, hydrology, geophysics, space physics, engineering and systems design. Turbulence studies in burning plasma will provide insights to studies of neutral fluid turbulence. Studies of magnetic reconnection, important for astrophysical systems, will be extended in a burning plasma program because of the increased separation of scales compared to present experiments, as well as the presence of energetic particles. The demanding constraints on the support technologies and instrumentation imposed by the high temperature, energy flux, and radiation of a burning plasma will be based on and stimulate technological advances in advanced technologies including robotics, materials, and remote information and data management. A burning plasma program will also contribute broadly to many of the nation's larger technology interests, including systems control, materials science, superconducting technology, and remote materials handling and systems maintenance. Finally, developing a predictive capability of burning plasmas that can contribute to the development of other fusion concepts will promote broad advances in diagnostics and computing.

A.5 The Burning Plasma Program Interaction with Industry and the International Community

The successful implementation of a burning plasma program will depend on the integrated efforts of creative scientists presently working at universities and national laboratories with those of their counterparts in high-technology industries. A burning plasma experiment will attract increased industrial participation in fusion research, thereby leading to innovations that will contribute to our nation’s broad science and technology infrastructure.

Fusion research has benefited immensely from international collaboration worldwide. The ability to independently reproduce experimental observations, to conduct non-dimensional studies over several experiments, and to have access to an extensive fusion database is crucial for advancing the understanding of fusion science and technology. In planning for a burning plasma experiment, the U.S. core program should maintain a strong international collaboration by taking advantage of complementary experimental facilities outside of the U.S., including new facilities on the horizon, to address key scientific issues relevant to the success of the burning plasma experiment.

B. FUSION DEVELOPMENT PATHS AND THE BURNING PLASMA EXPERIMENT

B.1 The Elements in the Fusion Development Path

A burning plasma experiment is a crucial and now missing step on a path to develop fusion as a practical source of energy. This goal is embodied in realizing a demonstration power plant (DEMO). A DEMO will employ all the physics and technologies needed in a commercial power plant at a scale readily extrapolated to commercial units, will put net electric power on the grid with reasonable availability, and will provide a licensing, cost, and public acceptance basis for commercial units.

A development path must include four major scientific elements (Snowmass Major Conclusion #5):

1. fundamental understanding of the underlying science and technology, and optimization of magnetic configurations,
2. plasma physics research in a burning plasma experiment,
3. high performance, steady-state operation,
4. development of low activation materials and fusion technologies.

1. Fundamental Understanding and Configuration Optimization

Snowmass Major Conclusion #6: **A strong science and technology program is needed to advance essential fusion science and technology and to participate effectively in and to benefit from the burning plasma effort. In particular, the development path for innovative confinement configurations would benefit from research on a tokamak-based burning plasma experiment.**

The Fusion Energy Sciences Program is providing basic plasma confinement physics knowledge from experimental, theoretical, and computational studies on a portfolio of magnetic configurations, plasma support technology research, and fusion technology research. Dramatic advances have been made in the last decade in the understanding of the physics of high-temperature plasmas confined by magnetic fields, both through more sophisticated plasma diagnostic measurements and through the greatly enhanced computational power now available to researchers. These efforts are critical because the innovations required for practical fusion energy can only arise from continued development of accurate physical understanding. Ultimately, the most attractive and competitive fusion power source is most likely to arise from efforts to more fully understand and control plasma behavior. Furthermore the scientific progress represented by this work has its own fundamental value.

Strong support for the fundamental understanding of the underlying science and technology for fusion energy will be essential throughout the time of development of fusion.

The burning plasma experiment, in order to play its crucial role in advancing fundamental understanding, must have the flexibility to study a broad range of scientific issues. Its measurement systems must be sophisticated enough to understand the plasma behavior and it must provide sufficient experimental time to allow thorough parameter scans and systematic studies.

Configuration optimization includes both the development of advanced tokamak (AT) operating modes and also studies of alternative configurations of the fusion plasma. While the designs of the three candidate burning plasma proposals are based on conventional tokamak physics already in hand, current tokamak research is now focused on the AT line, seeking to define the ultimate potential of the tokamak as a magnetic confinement system, with special emphasis on developing the physics of steady-state operation. In the decade until a burning plasma can begin operation, an advanced physics basis should become available and it can be expected that pursuit of advanced physics scenarios will become a major research focus in the burning plasma experiment. Superconducting non-burning tokamak facilities under construction abroad are designed to take this research into the steady-state regime in the next decade.

The Program must also support the advance of other confinement configurations, as candidates for fusion energy development. Study of these configurations also contributes to the fundamental understanding of plasma physics. In the U.S. there are active programs studying the Spherical Torus (the low aspect ratio limit of the tokamak), the Reversed Field Pinch (with very low external magnetic fields) and the Compact Stellarator (in which toroidal asymmetry is exploited for stability and steady-state operation). Smaller programs are underway investigating other innovative plasma confinement configurations. These programs are all aimed at providing an attractive confinement configuration for a DEMO or a future reactor.

2. The Burning Plasma Step

Snowmass Major Conclusion #1: **The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science. The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research.**

In the next generation of fusion research devices, an experiment is needed that can burn plasma, achieving fusion power gain of at least 5 in order to allow study of plasmas dominantly heated by the alpha particles produced in the fusion reaction. At a minimum, proposed burning plasma devices should have a high confidence of reaching this regime and being able to implement a full and rich experimental program studying such plasmas. Additional benefits would be provided by a burning plasma experiment that could be extended to longer pulse lengths and advanced tokamak research and to employ and demonstrate plasma and fusion nuclear technologies.

3. High Performance, Steady-state

It is desirable, although not essential, that a fusion power plant be able to operate in steady-state. A significant component of a world fusion development program should therefore focus on the plasma physics and technology issues of steady-state. Such research can be done in non-burning plasmas, but it would be very advantageous to be able to do it in a burning plasma. In the next generation of major national fusion experiments, a significant set of superconducting coil, long pulse, non-burning fusion devices appears available to carry forward this research line. Tore-Supra in Europe is an operating long pulse tokamak with a superconducting toroidal coil and LHD in Japan is an operating superconducting stellarator. Superconducting tokamaks under construction are the KSTAR in Korea, the HT-7U in China, and the SST in India. The proposed superconducting tokamak JT-60SC in Japan would be an important element of this research. The W-7X stellarator in Germany (under construction) will also make important contributions to long pulse issues.

4. Low Activation Materials and Fusion Technologies

Fusion energy technologies provide for plasma control; plasma fueling, heating, and current drive; magnets for plasma confinement; steady-state operation; safe handling and breeding of tritium; capture of fusion neutrons; and extraction of process heat and its eventual conversion into electricity. These technologies must be integrated to result in high reliability, availability, and maintainability in a practical, energy producing system with low residual radioactivity. Substantial development of the blankets that surround the plasma to capture the neutrons is necessary. Many options exist for choice of coolant, breeding material, structural material, blanket mechanical configuration, and operating parameters. The development of the knowledge base for use of low activation materials is particularly crucial. New facilities and dedicated test stands will be needed. A high fluence intense neutron source is needed to obtain lifetime irradiations of candidate fusion materials to develop irradiated materials property data. A high fluence volume neutron source is also needed to allow irradiation and operational development of full fusion nuclear technology components.

B.2 Role of candidate burning plasma experiments in fusion development paths

Set against the background of the above general development path requirements and relying on the report of the development path group from the recent Snowmass meeting, we offer the following evaluations of development paths. These paths assume that the US participates in the construction of only one of the proposed burning plasma experiments and that its program is successfully carried out.

ITER

A fusion development path with ITER as the burning plasma element would lead to the shortest development time to a demonstration power plant. The ITER device lies on the most direct path presently foreseen to fusion energy, through a superconducting coil toroidal experimental test facility (ETF) integrating physics and technology at power plant scale. ITER will provide a fully acceptable burning plasma experiment in terms of operational regimes and plasma measurement capabilities. Its operational flexibility and long pulse capability (about one hour) will provide an excellent laboratory for advanced tokamak physics development. The advanced physics basis that can be achieved in ITER will allow an advanced physics DEMO to follow ITER (Fig. 1). ITER will make a major contribution to the physics and technology of steady-state. It has a duty factor goal of 20% and its contribution, taken with the contributions of the other superconducting coil facilities listed above, will provide a firm basis for a steady-state DEMO. ITER will also provide significant initial tests of fusion nuclear technologies. On ITER, tritium handling experience can be gained and a modest number of fusion blankets can be shown to breed tritium and extract heat. ITER will enable fusion to demonstrate safety and licensing abilities at power plant scale.

Additional necessary facilities in this development path include an intense neutron source for irradiated materials data and a component test facility for high fluence blanket testing and development.

The development path in Fig. 1 indicates that the best confinement configuration will be selected for DEMO, taking into account results from ITER and the other development path elements, from the configuration optimization experiments, and from the anticipated advances in our computational ability to simulate integrated fusion systems. It is also possible that a tokamak DEMO might proceed in parallel with a large scale integration step (Experimental Test Facility ETF/DEMO) based on another configuration. Multiple national DEMOs might employ different configurations.

The ITER path requires an international agreement to be concluded to build ITER, bringing with it the advantages of cost sharing and program stability from the conclusion of such an agreement but the disadvantages of the complexity of realizing such an agreement and the complexity of an international project management system.

FIRE

FIRE would support a successful development path to fusion power. The FIRE development path seeks to address the burning plasma issues and advanced tokamak issues at the earliest time and the smallest necessary device scale. The FIRE device uses the cryogenic copper coil high magnetic field approach to obtaining high fusion gain in a much smaller, substantially less costly device. In this development path, FIRE's operational regimes and measurement capabilities will provide the basic burning plasma physics. FIRE has set ambitious goals in advanced tokamak physics. FIRE can provide a significant exploration of advanced tokamak physics, since its pulse length can be 1-3 current diffusion times in the plasma. FIRE's modest requirements in tritium handling and low neutron fluences do not require engaging power plant level safety and licensing issues.

The development path based on FIRE spreads the various development path needs over a number of facilities internationally (Fig. 2). While the ITER and FIRE development paths (Figs. 1 and 2) share all other development path items, the FIRE path places greater emphasis on some of these elements. The long pulse/steady-state research element will be done on the superconducting facilities listed above. The advanced tokamak physics basis will be obtained from FIRE, ongoing experiments, and the superconducting facilities. While the FIRE experiment would contribute to important plasma technology development like high heat flux plasma facing components and helium ash pumping, the FIRE development path places much more reliance on the set of fusion nuclear technology facilities discussed above. The component test facility will play a greater role in providing the fusion technology experience for the DEMO.

The FIRE development path approach will require a physics and technology integration step (Advanced ETF in Fig. 2) to follow FIRE and the associated development path elements. With the benefit of the completion of research on FIRE and the other research elements, the integration step following FIRE would be more advanced in physics and technical reach than ITER. The DEMO to follow this integration step would profit from this advanced technical basis. However, the deferral of the integration step may add time to the development path. It has been suggested, as indicated in the figure, that the Advanced ETF and the DEMO could be sequential devices or an upgrade of one device into the next within a single facility, perhaps reducing the additional time to about one-half of one machine generation.

At the decision point in Fig. 2, if the FIRE development path is successful, it is envisioned that a tokamak ETF followed by a DEMO would be built. An ETF/DEMO based on an alternate concept might also be done in parallel with or as an alternative to the tokamak ETF/DEMO.

The FIRE path envisions an internationally coordinated program with development path needs spread over major nationally run facilities, streamlining the management approach. However, the international community is concentrating at the present time on concluding the agreement to proceed with ITER.

IGNITOR

IGNITOR could be an element of a portfolio of experiments supporting ITER-based or FIRE-based development scenarios. The high field copper magnet IGNITOR device has a well developed design focused on the technical objective of providing an early pulsed burning plasma demonstration and exploration of the subsequent burn dynamics for about one current diffusion time at the lowest device cost. While IGNITOR's pulse length does not allow a thorough exploration of burn control or advanced tokamak modes, IGNITOR presents credible advanced performance scenarios to produce internal transport barriers on a transient basis.

Figure 1 — Development Path With ITER

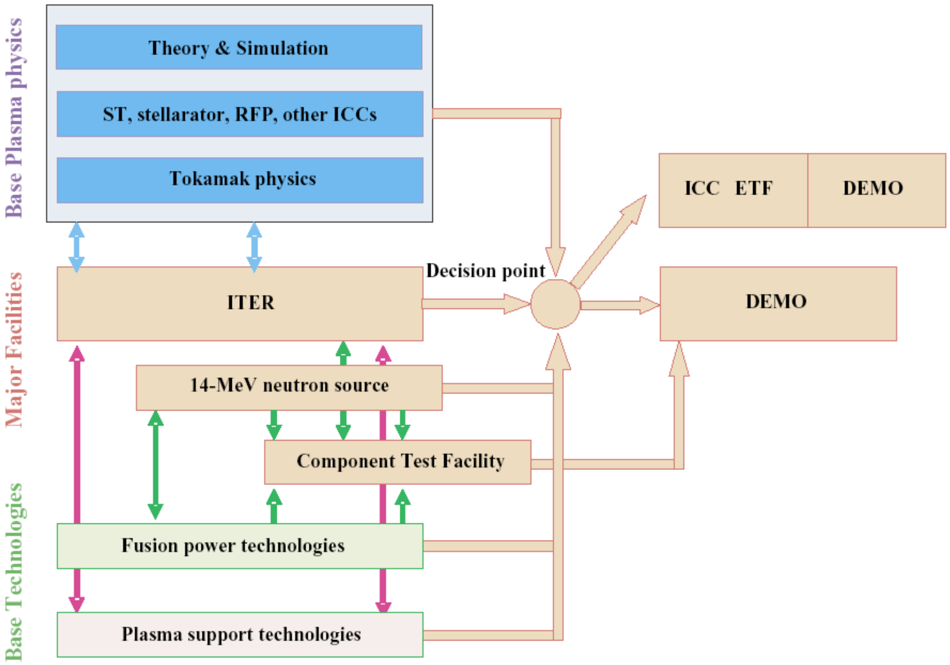
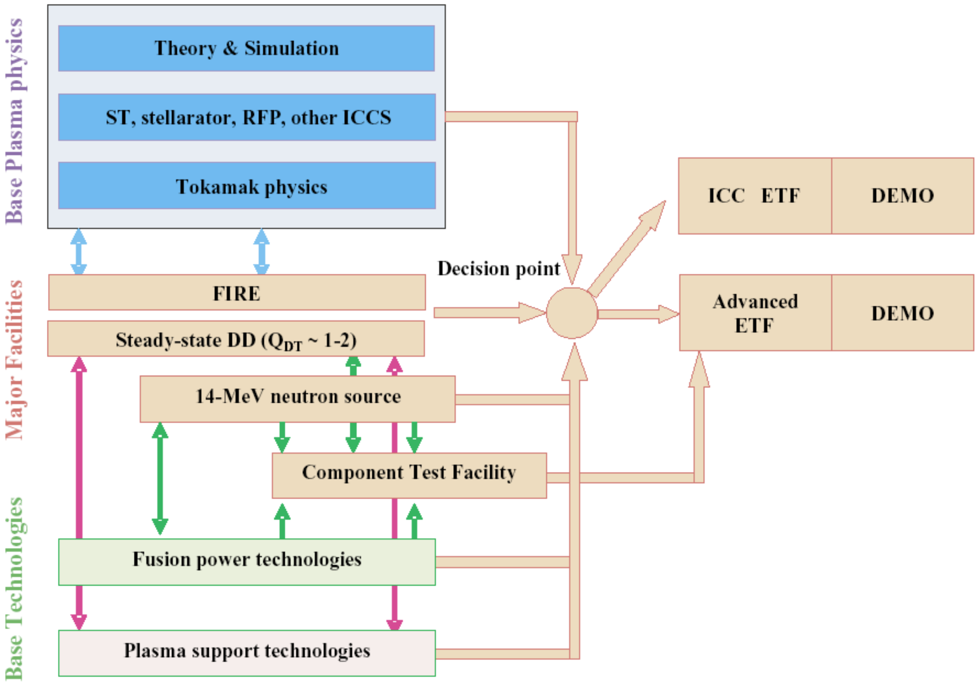


Figure 2 — Development Path With FIRE



C. POTENTIAL US ROLES AND INTERNATIONAL ASPECTS OF BURNING PLASMA

C.1 Background Information

This appendix identifies potential U.S. roles in selected options for burning plasma experiments (BPX). For each potential role, the report addresses topics such as the technical scope and relevance to U.S. capabilities and interests. No particular level of overall funding for participation in a BPX is assumed. Rather, this appendix provides a menu of roles to consider.

All three approaches within the U.S. burning plasma program include international aspects: U.S. participation in ITER, non-U.S. participation in FIRE, and U.S. participation in an Italian IGNITOR. For the purpose of guiding the negotiation of the international aspects of the U.S. burning plasma program, this appendix also addresses U.S. objectives for participation in the burning plasma program, forms of and priorities for international contributions to the three burning plasma approaches, and other aspects as relevant to the approach.

C. 2 Overall Guidelines and Principles for Assessing Potential Roles

The planning and preparation of any BPX initiative must engage a broad segment of the U.S. fusion scientific community to assure significant benefits to both the intellectual development of fusion science in the U.S. and the success of the burning plasma project. U.S. responsibilities and resources would fall into two rather broad areas: those needed to construct and equip the facility and those needed to operate and exploit it scientifically. Benefits derived directly from the former would occur in the nearer term and be more technological in character, although much scientific experience would be gained from the activities required for preparing for operation. Those from the latter would occur in the longer term and be more scientific, although much valuable technological experience would be gained from operation and maintenance of a burning plasma experiment. Among the BPX options currently under consideration -- building FIRE domestically but with some international participation, participating in ITER internationally or supporting IGNITOR in Italy[1] -- the relative share and balance of these two areas of activities borne by the U.S. would vary considerably. In a domestic construction project, the U.S. responsibilities would include nearly the full scope of design, fabrication, installation, testing, and operation. In any shared international endeavor, the responsibilities assumed by the U.S. would span design, construction, operation of equipment and exploitation of the facility, so as to assure maximum continuity and experience-in-depth. The U.S. would not be responsible for the full project. Nonetheless, whatever the final BPX option chosen, it must be anticipated that both types of activities will be undertaken.

Within the area of construction activities, several criteria for U.S. participation can be readily identified:

- building on U.S. experience, strength, and/or leadership;

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[1] IGNITOR proponents have also suggested the possibility of constructing an Ignitor-like device in the US.

- maintaining/increasing the breadth and depth of U.S. capability in fusion related technologies; and
- increasing U.S. industrial capacity in high-tech areas, especially ones important to fusion.
- confidence to complete task(s) within the allocated U.S. budget.

Certainly, anything undertaken should support the success of the overall project. If the project is international, similar criteria will likely be adopted by the other parties; in which case, the U.S. can assume that, in part, it will also be accepting some responsibilities that do not necessarily rank high as measured by these criteria but are nonetheless important to the project. For a domestic project, as noted earlier, the U.S. would naturally be responsible for all aspects.

Criteria for programmatic or operational activities include:

- providing opportunity to study burning plasma science under reactor-relevant conditions;
- advancing fusion science or technology in areas important to the U.S.;
- providing scientific experience relevant to other magnetic configurations;
- building on U.S. scientific strengths and providing synergy/continuity with existing U.S. facilities; and
- broadening U.S. expertise by providing opportunities not available on existing U.S. facilities.

Again, for an international project, other parties would likely have similar criteria. As a consequence, the U.S. might expect to lead in some areas and support in others, with data and other information being open to all participants.

C.3 U.S. Candidate Roles in Burning Plasma Experiments

A relatively comprehensive list of candidate roles and tasks for the U.S. is given in the table at the end of this appendix. These candidate roles/tasks cover a broad range of potential activities in terms of plasma physics, engineering and technology, and they cover potential activities in all phases of a burning plasma experiment. A brief task description is provided and then each potential task is characterized in several ways.

First, possible contributions to the U.S. plasma science program are identified and they are rated low, moderate or high. A "high" rating means that the task will make a very substantial contribution to the further development of plasma science and related progress towards fusion energy science. Similarly, contributions to U.S. fusion technology are identified and rated in the same manner. A "high" rating here means substantial contributions to the technology required for fusion energy. Finally, the existing US capability to perform the task is rated as high, moderate or low with some brief comments.

Lastly, possible U.S. roles with respect to the three main burning plasma options (ITER, FIRE, and IGNITOR) are described. These roles are only suggestive at this time and would be subject to much further discussion with the project leadership of each option.

C.4 Overall Objectives for U.S. Participation in the Burning Plasma Program:

In prioritized order, U.S. contributions to the Burning Plasma Program should address the following U.S. objectives:

(O1) to perform research on burning plasmas in the tokamak configuration, to contribute to the science base for the full range of toroidal confinement configurations,

(O2) to develop enabling technology that supports the burning plasma research and positions the US to more effectively pursue burning plasma research,

(O3) to advance fusion energy technologies, to prepare the technology base necessary for a demonstration fusion power plant,

(O4) to increase involvement of U.S. industry in the fusion program, both in design and fabrication of components for burning plasma experiments and in preparation for U.S. design and construction of a demonstration fusion power plant.

C.4.1 U.S. Participation in ITER Activities

Development of the U.S. negotiation plan for U.S. participation in ITER demands clear objectives, priorities and forms for contributions, and U.S. community "needs" and "desires", as well as considerations of the functional requirements for the ITER organizational and management structures.

U.S. ITER Activities should consist of 2 types:

(A1) U.S. ITER Project Activities, in which the U.S. addresses scope that is within the ITER construction project; examples include tokamak components, start-up diagnostics, superconducting strand, etc.

(A2) U.S. ITER Program Activities, in which the U.S. addresses scope that is outside the ITER construction project; examples include preparations for physics and technology research on ITER, the research/design/fabrication of post-construction scope such as advanced diagnostics and plasma control systems, and ITER operations.

Because performance of burning plasma research by U.S. researchers is the primary objective of U.S. participation in ITER (O1), it is important that the US and ITER organizational structures and processes enable and enhance opportunities for U.S. researchers to exploit ITER as a research tool, as a partner in the research activity. Elements that should be assured in the negotiations include:

(R1) a significant U.S. role in the decision-making regarding the ITER research program, including overall research directions and selection of experiments;

(R2) opportunities for U.S. researchers from all segments of the U.S. fusion community (universities, laboratories, and industry) to propose, plan, conduct and participate in experiments as members of the ITER research team;

(R3) opportunities for U.S. researchers to play leadership roles and participate in ITER's topical task forces, with access to all data from all available systems for all ITER experiments;

(R4) opportunities to apply theory and integrated modeling in design and analysis of experiments and in benchmarking of models against ITER data;

(R5) opportunities for the U.S. to develop and contribute equipment during the construction and operations phases of the device, and to have access to engineering data equal to that of all partners;

(R6) opportunities to propose/develop/design/fabricate/install/operate advanced diagnostics and enabling technology (e.g., plasma control tools) beyond the baseline;

(R7) opportunities to participate in fusion energy technology activities such as the development and testing of blanket modules.

U.S. Contributions to the ITER Project:

US contributions to ITER must meet both U.S. needs and ITER project needs. For example, it is unrealistic to plan that the US would be allowed to restrict its contributions to only those items considered most desirable to the U.S. Instead, U.S. contributions will likely be required to be balanced, contributing to a range of scopes that span from research-enabling products to conventional scope.

(C1) The highest priority should go to contributions that enable research on burning plasmas, research on burning plasmas and enabling technology (O1 and O2). This scope would include areas such as baseline diagnostics, plasma control, remote research tools, etc.

(C2) Second priority should go to fusion technologies (O3), particularly those in which the U.S. has special experience and interest and where U.S. industry could have a significant role (O4). This scope would include fusion-relevant products such as superconducting magnets, plasma-facing components, etc.

(C3) Third priority should go to high-tech non-fusion scope, such as more conventional technical industrial scope. Included would be power supplies, control and data acquisition, superconducting strand, etc.

Forms of US Contributions to the ITER Project:

The US should agree with the concept of having the US project contributions be made in four forms:

(F1) participation in the ITER Central Team and in the ITER U.S. Field Team; senior U.S. individuals would be seconded to the ITER Team and would play leading roles in the project activities; they would receive their direction from the ITER management.

(F2) "in-kind contributions", in which the U.S. commits to provide specific components such as several of the 85 procurement packages. For "in-kind" contributions, the U.S. would receive credit for the value assigned by the ITER

Legal Entity (ILE), but would be obligated to provide the product irrespective of the actual cost to the U.S. To assure completion of scope within the budget, the U.S. would have to include sufficient contingency in the budget estimates for "in-kind contributions".

(F3) "fund contributions", in which the U.S. controls but makes accessible a fund from which U.S. industry would be paid for ILE-specified and procured scope. For "fund contributions," the ILE would call for bids on specific work-scopes and the U.S. ITER Project Office would decide whether the requested work-scope would be eligible for payment from the US fund. If so, the ILE would issue the request for bids to U.S. (and other parties') industry and would evaluate the world's industrial bids. If a U.S. industry were selected, then the ILE would contract with the U.S. industry and the U.S. industry would receive payment from the U.S. fund as contractual milestones are met. (Note: the U.S. and the ILE must structure the procurements such that the ILE- and contractual-specifications and milestones are identical and the ILE must grant credit when the U.S. industry delivers products that meet the contractual specification.)

(F4) "cash contributions," in which the U.S. provides a small amount of cash to be controlled by the project for scope and expenses outside the negotiated procurement packages. This cash contribution is to provide required flexibility to the ILE. The cash will either be held in a U.S. fund or provided directly to the ILE, as negotiated.

It should be expected that construction scopes that are enabling and fusion technologies (C1 and C2) would be provided as "in-kind contributions" (F2). High-tech non-fusion scope (C3) could be provided either as "in-kind contributions" (F2) or as "fund contributions"(F3). Remaining, more conventional scopes (C4) should be provided as either "in-kind contributions" (F2) or "fund contributions"(F3).

Forms of U.S. Contributions to the ITER Program:

Because the first objective of the U.S. burning plasma program is the performance of research (O1) and the second objective focuses on enabling that research via contributions that extend the research capability of the facility (O2), it is expected that the US would engage in an accompanying ITER program. This accompanying program would entail several components, among them:

(P1) design and preparation of the ITER research infrastructure, including research decision-making processes and research tools,

(P2) participation in topical teams,

(P3) development and preparation of advanced diagnostic systems beyond the basic diagnostic set,

(P4) development and preparation of advanced plasma control tools,

(P5) development and prototyping of remote collaboration tools,

(P6) supporting research on existing facilities, and

(P7) theory, simulation and modeling.

This accompanying programmatic activity must be integrated with the U.S. domestic program and must be accessible to and involve all segments of the U.S. fusion community.

C.4.2 Non-U.S. Participation in FIRE Activities

FIRE would be primarily a U.S. national activity, but would invite non-U.S. participation. The U.S. would be responsible for the design/fabrication/assembly/test/operation of the FIRE facility and would manage the FIRE research program. Non-U.S. participation would enhance and/or accelerate the FIRE project and/or program.

FIRE Activities should consist of two types:

(A1) FIRE Project Activities would address scope that is within the FIRE construction scope; virtually the entire FIRE facility and associated support facilities would be within the FIRE project.

(A2) FIRE Program Activities would address scope that is outside the FIRE construction project; examples would include preparations for physics and technology research on FIRE, the research/design/fabrication of post-construction scope such as advanced diagnostics, and FIRE operations.

Non-U.S. Participation in FIRE Project Activities

There would be an opportunity for non-U.S. institutions and companies to participate in the design and construction phase of FIRE. There may be unique areas of expertise and capability where a non-U.S. party would wish to participate as a collaborator or as a contractor to the FIRE project. The details of participation would be negotiated on a case by case basis.

Non-U.S. Participation in FIRE Research

Non-U.S. participants in the FIRE would likely focus on burning plasma research and on enabling technology. Elements would include:

(R1) participation by non-U.S. researchers in FIRE’s research activities

(R2) opportunities for non-U.S. researchers to lead and participate in FIRE’s topical task forces

(R3) the right for non-U.S. researchers to propose experiments

(R4) non-U.S. researcher participation in experiments with access to all data related to those experiments

(R5) proposal/development/design/fabrication/installation/operation of advanced diagnostics and enabling technology (e.g., plasma control tools) beyond the baseline

(R6) the opportunity for non-U.S. participants to perform theory and integrated modeling both in design and analysis of experiments

(R7) joint work by non-U.S. participants on supporting experiments on non-FIRE facilities

(R8) non-U.S. participation in fusion technology activities.

Non-U.S. Contributions to FIRE:

Non-U.S. contributions to the FIRE project must meet both non-U.S. needs and FIRE project and program needs. Non-U.S. contributions to FIRE would be in the form of “in-kind contributions”, in which the non-U.S. party commits to provide specific products in exchange for the opportunity for participation in FIRE research.

C.4.3 U.S. participation in an Italian IGNITOR

U.S. participation in an Italian IGNITOR would be much like the traditional U.S. collaboration on international facilities such as JET, JT6-0U, etc. The U.S. community would identify key areas of interest and would propose to the DOE/OFES a package that would include a balance of research participation and supporting hardware. This package would be discussed with the Italian host of the IGNITOR facility and might result in a formal proposal to the OFES for funding to participate in IGNITOR in the specified manner. These perspectives are addressed in this part of the white paper.

Performance of burning plasma research by U.S. researchers would be the primary objective of U.S. participation in IGNITOR. U.S. and IGNITOR organizational structures and processes must enable opportunities for the U.S. researchers to exploit IGNITOR as a research tool, as a participant in the research activity. Elements that must be assured in the negotiations include:

(R1) the right for U.S. researchers to propose experiments

(R2) U.S. researcher participation in experiments with access to all data related to IGNITOR experiments

(R3) proposal/development/design/fabrication/installation/operation of advanced diagnostics and enabling technology (e.g., plasma control tools) both in and beyond the baseline

(R4) the opportunity to perform theory and integrated modeling both in design and analysis of experiments

(R5) U.S. participation in fusion technology activities such as the development and testing of high-field RF systems

U.S. Contributions to IGNITOR:

U.S. contributions to IGNITOR would be focused in areas such as baseline and advanced diagnostic systems, RF heating components, the pumping system, and the fueling system. The U.S. contributions would be “in-kind contributions,” in which the U.S. commits to provide specific components in exchange for access to IGNITOR for associated research. The U.S. would be obligated to provide the product irrespective of the actual cost to the U.S. To assure completion of scope within the budget, the U.S. must include sufficient contingency in the budget estimates for “in-kind contributions.”

US Candidate Roles In Burning Plasma Experiment

Candidate Task	Task Description	Contributes to US Plasma Science	Contributes to US Fusion Technology	Existing US Expertise	ITER --- Potential US Role	FIRE --- Potential US Role	IGNITOR --- Potential US Role
Plasma Diagnostics	Design, fabricate and operate instrumentation that enables studies of plasma behavior; design both instruments and supporting infrastructure (associated shielding, components such as mirrors and windows and radiation-tolerant cable, etc.)	High - key enablers of plasma understanding that also position the provider to play leading roles in plasma studies	Moderate - Plasma diagnostics are an enabling technology applicable to a wide range of potential spin-offs;	High - The US is a world leader	US should emphasize diagnostics that enhance understanding and enable knowledge-based innovation; Diagnostics R&D and design/fabrication is a key method for involvement of physics community during the design and construction phases	US has the lead responsibility and would define the scope of the diagnostic systems. This would be a major scientific driver for long term University and National Laboratory programs in the US. There would be some international collaboration e.g., NINB diagnostic neutral beam.	US could lead in sub-set of diagnostics that enhance understanding and enable knowledge-based innovation; Diagnostics R&D and design/fabrication is a key method for involvement of physics community during the design and construction phases
Plasma Control Systems	Provide for basic control of plasma equilibrium parameters (current&pressure profile, fueling, heating,etc) and active control of MHD stability. Includes design and operation of data acquisition and real-time computer analysis to support broad Plasma Control mission.	High - central to enabling research and applying BP experience to other configurations	Low	High - US a world leader	Design Lead/Integrator/Equipment Supplier followed by co-leadership role in operations and analysis. Would naturally couple to key active control diagnostics, e.g. (q-profile, MHD,…)	US would define and provide for basic control of plasma equilibrium parameters (current&pressure profile, fueling, heating,etc) and active control of MHD stability. Includes design and operation of data acquisition and real-time computer analysis to support broad Plasma Control mission.	Design Lead/Integrator/Equipment Supplier for selected control systems followed by potential leadership role in operations and analysis in (tbd) areas.
Plasma Performance Modeling	Develop and apply a wide variety of plasma and system modeling codes to predict performance, analyze data, test understanding, etc.	High – central to component design and applying BP experience to other configurations	Low	High – US a world leader	Integrator/participant of plasma modeling effort US would develop and apply a wide variety of plasma and system modeling codes to predict performance, analyze data, and test understanding. Strong coupling with the ongoing program.	US would define and develop and apply a wide variety of plasma and system modeling codes to predict performance, analyze data, test understanding. Strong coupling with the ongoing program.	Integrator/participant of plasma modeling effort
Analyis of AT Modes	Draw on extensive AT experience to develop AT scenarios for PBs, analyze results, etc.	High – central to BP higher performance operations and research	Low	High – US a world leader	Integrator/participant of AT physics program	The US is the leader internationally. The US fusion community would define the FIRE AT program, and has the responsibility for all aspects.	Experimental lead of AT physics program

Candidate Task	**Task Description**	**Contributes to US Plasma Science**	**Contributes to US Fusion Technology**	**Existing US Expertise**	**ITER --- Potential US Role**	**FIRE --- Potential US Role**	**IGNITOR --- Potential US Role**
Experimental Planning	Participate in the planning for the experimental program, including scenario development, projections of a burning plasma performance based on recent experimental and theoretical results, revising the physics requirements in response to new results and engineering issues and eventually, development of experimental proposals.	High - addresses both which experiments the US will conduct, possible facility upgrades and whether the facility will be able to address key issues.	Low - except through supporting the experimental program and addressing engineering issues.	High - US is a world leader.	US needs to be an integral member of this activity. For ITER, US needs to participate both in the international and participants teams.	US has the lead in defining the FIRE Experimental Program, and would be responsible for executing the experimental program. This would be strongly connected to the existing program and to the US vision for a fusion reactor.	US participation in experimental planning would be desirable.
Remote Participation	Apply state-of-the-art information and computer technology to enable execution of experiments, access to data, etc., from dedicate remote sites.	Moderate – enabling technology	Moderate – important technology with other applications	High – an emerging area with strong US base	Architect and supplier of ITER remote access system. The US has been a long standing leader in this area. State-of-the-art information and computer technology to enable execution of experiments, access data, etc., from US co-laboratory sites.	The US has been a long standing leader in this area. State-of-the-art information and computer technology to enable execution of experiments, access to data, etc., from US Co-Laboratory sites.	
Computer Applications	Supply the computer hardware necessary for control, data acquisition and analysis, etc.	Low – enabling technology	Low	High – US a world leader.	Architect and supplier of computer hardware	Define all requirements and supply the computer hardware and software necessary for control, data acquisition and analysis, etc.	
SC Wire and Magnet Systems	Design, fabrication, installation and operation of superconducting magnet system including toroidal and poloidal coils.	Low - only indirectly through enabling a major experiment.	High - provides fabrication capability of essential item.	Yes, but industrial team disassembled after the ITER EDA.	All potential worldwide venders of SC wire may be needed to meet ITER construction schedule. This would be an early procurement item.	Define all requirements and supply the room-temperature magnet systems for FIRE	
PFC Components	Design, fabrication, installation and operation of divertor and first wall components.	Moderate-High. Strong involve-met of US edge physics com-munity could be envisioned.	High. Provides opportunity for reinvigoration of high-heat-flux component de-development effort in US.	Yes, Tungsten brush approach being adopted for ITER is a US innovation.	The ITER divertor is composed of modules, therefore it would be reasonable to fabricate a fraction of the total, e.g. half. This would ensure US entry into the edge physics arena and maintain a US position in the technology.	The FIRE PFCs are aimed at high power-density reactor-relevant applications. For FIRE, The US would be responsible for all aspects of design, construction, installation and operation of the divertor modules and interfaces with other systems in an integrated manner.	Ignitor is a limiter experiment. US involvement would improve database & knowledge base in edge-physics arena to compare divertor-limiter operations.

Candidate Task	**Task Description**	**Contributes to US Plasma Science**	**Contributes to US Fusion Technology**	**Existing US Expertise**	**ITER --- Potential US Role**	**FIRE --- Potential US Role**	**IGNITOR --- Potential US Role**
First Wall Shield	Design, fabricate and install integrated shield/first-wall blanket modules	Low - Enabling Technology	High-Technologies involved are important for follow on DT machines.	High - Fabrication methods are within capabilities of many US vendors. US has special capability in area of Beryllium fabrication and bonding.	As with divertor, blanket is composed of modules whose fabrication could be shared with other ITER participants. US industry could gain technological capability for shield/first-wall fabrication at a fraction of total blanket cost.	The US would design, fabricate and install a first wall with power-densities approaching reactor levels (2.5 MWm-2) with inertial cooling for the first phase and possibly actively cooled first wall in an upgrade phase.	
Blanket Test Module	Design, fabricate and test breeding blanket module(s)	Low.	High - Machines beyond ITER on fusion development path will require tritium breeding (regardless of concept).	Moderate - US blanket development program has shrunk in the last several years due to shift in emphasis to plasma science. But US capability and interest persist.	Each ITER participant plans its own module development program. Tritium breeding ratio greater than unity using attractive materials and cooling methods will be as fundamental to the success of fusion energy as achieving high gain. US could take advantage of ITER's unique neutron flux and fluence capability to develop and test environmentally attractive blanket concepts. (Note: Lifetime issues will require separate facility.)	Proposals to test blanket test modules at high power densities on FIRE have been received, and will be developed and evaluated.	
Heating and Current Drive	**IC**-Design, fab., test, operate an Ion Cyclotron system for heating and current drive	High - if used for current drive and profile control	High	High; world-class technology, physics expertise.	Collaborate/lead design; prototype fab. & test. EU likely other main contributor.	**IC**-Design, fab., test, operate an Ion Cyclotron system for heating and current drive	Electromagnetic, mechanical and thermal design analysis. Absorption calculations and heating scenario development. Prototype testing. Operation and optimization of ICRF heating system.
	LH-Design, fab., test, operate a Lower Hybrid system for heating and current drive	High - if used for current drive and profile control	High	High - US has been world leader in this area. LH is a major theme in the future C-Mod program.	Collaborate w. EU (primarily); particular US expertise on innovative launcher design.	**LH**-Design, fab., test, operate a Lower Hybrid system for heating and current drive for the AT phase.	NA
	EC-Design, fab., test, operate an Electron Cyclotron system for heating and current drive	High - if used for current drive and profile control	High	High- good launcher expertise, source R&D	Source-Collab. w.JA, EU on source design & testing. Launcher- Collab/lead design	**EC** - not currently planned. Proposals for EC were advanced for CIT/BPX and informally for FIRE. These will be evaluated.	NA

Candidate Task	**Task Description**	**Contributes to US Plasma Science**	**Contributes to US Fusion Technology**	**Existing US Expertise**	**ITER --- Potential US Role**	**FIRE --- Potential US Role**	**IGNITOR --- Potential US Role**
	NB-Design, fab., test, operate a Neutral Beam system for heating and current drive	High - major heating source at present	Moderate	Low- no NB research at present in the US.	Effective collaborations in place with JA. Present LOE precludes major participation. Consult, review designs main contribution.	**NB**-Design, fab., test, operate a Neutral Beam system for edge plasma rotation. Possible collaboration with Japan on NINB for diagnostics.	NA
Fueling, Vacuum Pumping and Disruption Control	Design, fabrication, installation and testing of fueling system components (pellet injectors) and disruption mitigation system. Design, fabrication and test prototype (fueling and disruption mitigation systems) to optimize reliability. Analysis of fueling, pumping and disruption mitigation.	High – central to BP high performance, AT ops. Enabling technology for central Tritium fueling and low wall inventory.	High - fueling system is an enabling technology applicable to a wide range of confinement concepts. The disruption control system is a unique technological requirement that needs to be further developed on existing devices.	Substantial US expertise. US played leading role in fueling during ITER EDA. World class technology, physics expertise. Collaborations with EU and JA.	Collaborate/lead design; prototype fab, test and operate. EU likely other main contributor. A full scale prototype would be necessary for testing of components/systems and evaluation of reliabilities. The prototype could be implemented in the US.	Design, fabrication, installation and operation of fueling system components (pellet injectors). Develop, design, construct and operate an integrated disruption mitigation system (IDMS) that includes the sensors, actuators and plasma simulator feedback control. Test on existing US tokamak experiments.	Design, fabrication, and testing of pellet injectors for outside or vertical launch. Design, fabrication and testing of disruption mitigation system. Operation and optimization of pellet fueling system for the control of plasma profiles and for the exploration of enhanced confinement regimes. Operation and optimization of disruption prediction and mitigation system.
Vacuum Vessel	Design, fabrication, installation and monitoring of vacuum vessel. Provide design code acceptable to regulators	Low – enabling technology	Moderate - provides design code for subsequent burning plasma experiments & demo	Industrial expertise for fab plentiful, ASME logical choice to develop design code, high capability in disruption loads, stress analysis, neutronics	US contribution should be high with respect to design code development, Could be high with respect to assembly (automated welding).	Design, fabrication, installation and operation of vacuum vessel. Choice of materials and design codes to be consistent with requirements envisioned for future demos or test reactors.	Mechanical, thermal and disruption load analysis. Assembly and automated welding.
Tritium Systems	Design, fabrication, installation and operation of tritium systems.	Low – enabling technology	High - critical technology for the program and future DT experiments.	High, US a world leader.	US could provide design expertise, hardware and operational support for ITER.	Design, fabrication, installation and operation of tritium systems. Systems will be specialized to reduce inventories, and will be strongly coupled to US tritium experience and infrastructure.	

Candidate Task	Task Description	Contributes to US Plasma Science	Contributes to US Fusion Technology	Existing US Expertise	ITER --- Potential US Role	FIRE --- Potential US Role	IGNITOR --- Potential US Role
Remote Handling	Design, development, procurement, testing, installation and operation of remote handing systems and tooling. Also design and testing of remote handling compatible component interfaces.	Low - enabling technology	High - required for inspection, maintenance and modification of BPE components	High, US a world leader in RH technology and an experienced partner in international fusion experiments.	US contribution should be high with lead role for portion of remote handling systems / machine interfaces, and participation in international team In-vessel metrology, advanced manipulator design and controls, VV remote welding, hot cell systems and RH compatible components of particular strength.	Design, development, procurement, testing, installation and operation of remote handing systems and tooling. Also design and testing of remote handling compatible component interfaces.	In-vessel metrology, advanced manipulator design and controls, VV remote welding, hot cell systems and RH compatible components. Design of some remote handling systems / machine interfaces.
Engineering Design	Provide analysis, design expertise and R&D needed for design of all engineering systems. ITER and IGNITOR have completed all design activities except for site specific details. FIRE - conceptual, preliminary and final design need to be carried out.	Low - enabling technology	High - provides skills base for future reactor designs	Laboratory and industrial expertise exists, but has been dispersed from fusion program due to lack of US construction of a major magnetic fusion project in over 15 years.	For an international project the US contribution could include support for site specific activities and global analyses such as disruptions, neutronics, safety, etc. For domestic project all aspects of an integrated engineering design are involved.	Provide analysis, design expertise and R&D needed for design of all engineering systems. The conceptual, preliminary and final design activities need to be carried out.	Support for global analyses such as disruptions, neutronics, safety, etc. and some site specific activities. Cryostat design and analysis?
Central Team Staff	Provide both engineering and physics design staff to a central team in both design and operating phases.	High. Involvement in Central Team essential for planning and executing experimental program.	High. Experience gained in designing and fabricating a BPX class device invaluable for future steps.	High. US was a strong contributor to ITER EDA. Expertise still exists but a new project badly needed.	Engineering: Lead and supporting roles in several WBS areas. Physics: Topical area leaders and support., e.g., RF Divertor/Edge, MHD, Transport, etc.	Provide management, system engineering, engineering, and physics staff for the project team in both design and operating phases.	Engineering: Lead and supporting roles in several WBS areas. Physics: Topical area leaders and support., e.g., RF , fueling, MHD, Transport, etc.
Safety Analysis	Perform a variety of safety analysis and supporting R&D to facilitate burning plasma experiment.	Low.	High. Safety is critical to realization of fusion energy.	Substantial. US played leading role in safety during ITER EDA.	US could play a leading role in this area through international team and domestic support activities.	Perform the full range of safety analysis and supporting R&D to enable a burning plasma experiment.	
Materials Support	Provide a variety of materials engineering support through assessments and analysis for BP options.	High for PFC materials issues.Low for other materials.	High. Materials are critical to fusion energy.	Substantial. US has laeding PFC and fusion materials expertise.	US could play a leading role in this area through international team and domestic support activities.	Provide a variety of materials engineering support through assessments and analysis for BP options.	
Machine Assembly	Assemble the machine to close tolerances and ensure that the machine can be remotely maintained and disassembled.	Low- critical for operations.	High - critical to begin operations.	US was involved in the design of ITER and is responsible for the design for FIRE.	US could be a contributor in this area for ITER.	Assemble the machine to close tolerances and ensure that the machine can be remotely maintained and disassembled.	

Candidate Task	Task Description	Contributes to US Plasma Science	Contributes to US Fusion Technology	Existing US Expertise	ITER --- Potential US Role	FIRE --- Potential US Role	IGNITOR --- Potential US Role
Cryostat	Design and fabricate large-scale cryogenic vessel	Low	Moderate .	Low/medium	Relatively low tech item. Minimal interest for US.	Design and fabricate large-scale cryogenic vessel	
Machine Support Structure	Design and fabricate large-scale structure	Low	Moderate.	High	Relatively low tech item. Minimal interest for US.	Design and fabricate large-scale structure.	
Power Supplies	Design and fabricate large-scale power system	Low	Moderate	High	Relatively low tech item. Minimal interest for US.	Design and fabricate large-scale power system. Possible reuse of capabilities at an existing US site.	
Land and Buildings	Host responsibility	Low	Low	not applicable		Possible reuse of capabilities at an existing US site. Site might also be the first step in a US Fusion Energy Laboratory site	
Water cooling, cryogenics, waste-handling, utilities, site electrical power	Design and fabricate large-scale conventional systems	Low	Low	High	Relatively low tech item. Minimal interest for US.	Design and fabricate large-scale conventional systems. Possible reuse of capabilities at an existing US site. Site might also be the first step in a US Fusion Energy Laboratory site	
Project/ Construction/ Environmental/ Safety Management	Integrated management of large-scale construction project	Low	Low	High	US could play role in project management. Safety is responsibility of host.	Full responsibility for integrated management of large-scale fusion construction project In preparation for US integrated fusion test reactor.	
Systems Engineering	Design of integrated system	Low	Moderate	High	US could play a role in project engineering/integration.	Design of all aspects of an integrated fusion system.	

D CHARGE LETTER

Department of Energy
Washington, DC 20585

February 22, 2002

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

Dear Professor Hazeltine:

In response to our earlier request, FESAC has provided me with clear advice on the scientific status of burning plasma physics. FESAC has recommended that the Department proceed apace toward decisions that would enable the U.S. fusion energy sciences community to address experimentally the important scientific issues involved in burning plasma physics.

In accordance with the FESAC recommendations, we are supporting the Fusion Summer Study later this year, with its focus on a detailed examination and assessment of the benefits to be achieved in the various possible approaches to an experimental program in this field.

The next step in this process is for FESAC to establish a high-level panel that would use the results of the Summer Study to recommend a strategy for burning plasma experiments. This panel's report should show how ITER would fit into the U.S. fusion program, if it were to go forward with our participation. The panel should also indicate how a FIRE or Ignitor type of device would fit in our program, if ITER were not to go forward. The panel's proposed strategy should provide flexibility for us to join ITER, should the Administration decide to enter negotiations, and if we are able to negotiate acceptable terms, and that allows us to decline to join if the terms are not acceptable to both the community and the Administration.

Given the importance of a timely decision process, I ask FESAC to have the panel complete its report as quickly as possible after the Summer Study in July. It is important that FESAC itself review the panel report and send me the full Committee's recommendation by the end of the summer, in September 2002.

In parallel, we will ask the National Research Council to prepare to review FESAC's recommendations and report to us with their assessment by the end of 2002.

This set of actions will provide the Department with the essential fusion community view, as well as an external review, on the critical question of how to pursue burning plasma physics.

Thank you in advance for your efforts to provide your report to us on a timely basis.

Sincerely,

James F. Decker
Acting Director
Office of Science

E. FESAC Panel on the Strategy for a Burning Plasma Program

Charles Baker, *University of California, San Diego*
David Baldwin, *General Atomics*
Herbert Berk, *University of Texas at Austin*
Riccardo Betti, *University of Rochester*
James Callen, *University of Wisconsin – Madison*
Vincent Chan, *General Atomics*
Bruno Coppi, *Massachussetts Institute of Technology*
Jill Dahlburg, *General Atomics*
Steven Dean, *Fusion Power Associates*
William Dorland,* *University of Maryland*
James Drake, *University of Maryland*
Jeffrey Freidberg, *Massachussetts Institute of Technology*
Robert Goldston, *Princeton Plasma Physics Laboratory*
Richard Hawryluk, *Princeton Plasma Physics Laboratory*
Richard Hazeltine, *University of Texas at Austin*
E. Bickford Hooper, *Lawrence Livermore National Laboratory*
Amanda Hubbard, *Massachussetts Institute of Technology*
Thomas Jarboe, *University of Washington*
Joseph Johnson, *Florida A & M University*
Martin Lampe,* *Naval Research Laboratory*
John Lindl, *Lawrence Livermore National Laboratory*
Grant Logan, *Lawrence Livermore National Laboratory*
Earl Marmar, *Massachussetts Institute of Technology*
Michael Mauel, *Columbia University*
Kathryn McCarthy, *Idaho National Engineering and Environmental Laboratory*
William McCurdy,* *Lawrence Berkeley National Laboratory*
Dale Meade, *Princeton Plasma Physics Laboratory*
Wayne Meier, *Lawrence Livermore National Laboratory*
Stanley Milora, *Oak Ridge National Laboratory*
George Morales, *University of California at Los Angeles*
Farrokh Najmabadi, *University of California, San Diego*
Gerald Navratil, *Columbia University*
William Nevins, *Lawrence Livermore National Laboratory*
David Newman, *University of Alaska at Fairbanks*
Ronald Parker, *Massachussetts Institute of Technology*
Francis Perkins, *General Atomics*
Cynthia Phillips, *Princeton Plasma Physics Laboratory*
Miklos Porkolab, *Massachussetts Institute of Technology*
Stewart Prager (Chair), *University of Wisconsin – Madison*
Marshall Rosenbluth,* *University of California, San Diego*
Ned Sauthoff, *Princeton Plasma Physics Laboratory*
Kurt Schoenberg,* *Los Alamos National Laboratory*
John Sheffield, *Oak Ridge National Laboratory*
Ronald Stambaugh, *General Atomics*
Edward Synakowski, *Princeton Plasma Physics Laboratory*
George Tynan, *University of California, San Diego*
Nermin Uckan, *Oak Ridge National Laboratory*

*Not present at panel meeting in Austin, Texas

F. FESAC Burning Plasma Strategy Panel Meeting
August 6 – 8, 2002
Applied Computational and Engineering Sciences (ACES) Building
Austin, Texas

BACKGROUND

August 6

8:30	Welcome	R. Hazeltine
8:35	The Meeting Plan	S. Prager
9:00	Snowmass Results and Discussion	G. Navratil/N. Sauthoff
10:30	Break	

TOPICAL ISSUES

10:45	Topical Breakout Groups (S & T, Development Path, International Collaboration, Integration)
12:30	Lunch
1:30	Reports of Topical Breakouts
3:30	Break

STRATEGY

3:45	Strategy Breakout Groups (4 randomly constituted groups)
5:45	Adjourn
6:15	Reception
7:45	Synthesis Group Meeting

August 7

8:30	Reports from Strategy Groups
10:30	Break
10:45	Strategy Groups/Synthesis Group
12:00	Lunch/Synthesis Group Meeting
1:00	Report of Strategy Groups
2:00	Report Writing – Section III/Synthesis Group Meeting
3:15	Break
3:30	Report of Synthesis Group – strawman strategy
4:00	Discussion of Strawman Strategy
6:00	Adjourn
6:30	Synthesis Group meeting

August 8

8:30	Report from Synthesis Group – draft strategy
	Discussion of draft
	Agreement on key strategy
10:30	Report writing
12:00	Lunch
2:00	Distribution of draft report and discussion
3:15	Break
3:30	Discussion
5:00	Adjourn

Topical Groups

Science and Technology: Nevins (co-chair), Hawryluk (co-chair), Berk, Betti, Callen, Coppi, Dorland, Hubbard, Meade, Perkins, Porkolab

Development: Stambaugh (chair), Dahlberg, Freidberg, Goldston, Lindl, Marmar, McCurdy, Milora, Najmabadi, Navratil, Schoenberg

International: Baker (chair), Baldwin, Dean, Jarboe, Johnson, Logan, McCarthy, Parker, Sauthoff, Sheffield, Uckan

Integration: Mauel (chair), Chan, Drake, Hooper, Morales, Newman, Phillips, Synakowski, Tynan

Synthesis Group

Prager (chair), Baker, Berk, Betti, Chan, Hooper, Lindl, Marmar, Navratil, Sauthoff, Schoenberg