FIRE Physics Validation Review (PVR)

Germantown, March 30-31, 2004

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Introduction:

On March 30-31, 2004 the OFES convened a panel of technical experts with a broad range of fusion science and engineering expertise to give DOE their individual assessments of the status of the physics embodied in the design of the Fusion Ignition Research Experiment (FIRE). The membership of this panel and the charge to this panel is included in attachment 1. This report constitutes the DOE's assessment of the physics used in the design of FIRE.

Background:

In FY 1999 the OFES initiated the FIRE study and design effort. At the time the US was in the process of getting out of the ITER EDA, and it was felt that the US needed to look at what the other options were for exploring burning plasmas. Dr. Dale Meade was chosen to lead the effort to look for affordable burning plasma experiments and he pulled together a highly qualified and experienced national team to conduct the study and design effort. The cost of this effort to date is about $12M. In October 2003, the National Academy of Sciences advised DOE: "If the ITER negotiations fail, the United States should continue, as soon as possible, to pursue the goal of conducting a burning plasma experiment with international partners".

Assessment:

The stated mission of the FIRE project is to "attain, explore, understand and optimize fusion-dominated plasmas". The product of their work, and their contributions to and leadership within the overall burning plasma effort, is outstanding. Below are answers to the four questions posed to the review committee.

Are missions and objectives identified by FIRE appropriate to answer the critical burning plasma issues in a major next step experiment?

The Fusion Energy Sciences Advisory Committee (FESAC) Report on "A Burning Plasma Program Strategy to Advance Fusion Energy" (2002) declares that 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. Since the time that FESAC last looked at FIRE, the mission and objectives of FIRE are mostly unchanged, as are the burning plasma physics issues that await investigation. The NRC Assessment "Burning Plasma: Bringing a Star to Earth" (2004) affirmed the validity of the burning plasma objective.

Is the proposed physical device sufficiently capable and flexible to answer the critical burning plasma science issues proposed above?

Since the 2002 FESAC report the evolution of the FIRE design has continued to strengthen the ability of FIRE to contribute to burning plasma science. Specifically,

- Investigation of FIRE operating scenarios has uncovered advanced tokamak modes of operation in which the pulse length can be 3 – 5 current relaxation times (vs. 1- 3, reported at the 2002 Snowmass (web.gat.com/**snowmass**) Summer Study). Achievement of the longer pulse requires trade-offs. It is obtained by operating at reduced current, magnetic field, and plasma temperature, so as to diminish the current relaxation time. In addition, the alpha particle slowing down time is decreased, diminishing the energetic alpha population. Nonetheless, it represents added AT capability (without the need for superconducting coils) and is a positive development.

- Increased magnet cooling has enhanced the full magnet-power shot rate to 1 per hour (vs. 1 per 3 hours reported at Snowmass)

- Modeling of FIRE operating scenarios with a time dependent code, 1-1/2D in space (evolving flux-surface-averaged quantities) has identified interesting AT scenarios.

- With advanced tokamak operation, for which the magnetic field and plasma current are reduced, it may be possible to obtain 5000 full fusion power shots. This possibility is being evaluated as part of the pre-conceptual design.

- The FIRE team has confirmed the expectation that neutral beam injection for plasma heating, fueling, and flow and current drive, is not feasible in FIRE.

However there remains a concern while FIRE may explore many aspects of burning plasmas it may be unable to address reactor-relevant Toroidal Alfven Eigenmodes with multiple overlapping higher-n modes.

What areas are deficient and what remedies are recommended?

FIRE-specific areas that would benefit from further pre-conceptual design work by the FIRE team include

- *Investigation of FIRE operating scenarios in which alpha particle instabilities can be excited.* An issue discussed at Snowmass was whether the electron temperature would be sufficiently high to observe the instabilities. This issue still requires further work.

- *Design of a generic port plug.* This is a design feature that mixes many considerations, including those related to diagnostics, RWM feedback coils, and heating and current drive.

- *Modeling of n > 1 resistive wall modes.* The FIRE team has assessed the beta limit for the feedback-stabilized n = 1 mode. However, the n > 1 modes have a lower beta limit with an ideal wall. The team should model the n > 1 modes with the Valen code to assess the stability limits with feedback stabilization. They should also determine what the stability limits are for n > 1 RWMs utilizing only active feedback stabilization of the RWM (assuming no externally-driven rotation). Do these intermediate-n modes change the AT scenario operating point? How much does FIRE-AT performance suffer if RWM feedback is ineffective?

- *Modeling stabilization of the (2,1) and (3,2) neoclassical tearing modes by lower hybrid current drive.* The team should perform a simple scoping study to specify the RF current drive requirements.

- *Prevention of freezing of water in close proximity to liquid nitrogen cooled coils.* Since many structures use water for cooling, the proximity of large structures at liquid nitrogen temperature presents the prospect of freezing, which would cause significant problems. Approaches for insuring isolation could be examined, at least in a preliminary way, especially for the water in the vacuum vessel, which is probably at highest risk.

- *Simultaneous Stabilization of 3/2 and 2/1 modes.* For the baseline scenario with q(0) near 1, both the 3/2 and 2/1 tearing modes could be problematic in the presence of sawteeth and ELMs. Thus, for this scenario, it may be necessary to modify the equilibrium q profile at several rational surfaces simultaneously. The issue is whether the current drive system, diagnostics, and controls are capable of doing this.

- *LHCD in the startup phase.* The LHCD is supposed to allow access to a favorable and nearly stationary q profile in the early discharge phase of AT regimes for many current relaxation times. Is the launch spectrum control flexible enough to achieve the desired driven current profile evolution to achieve this state?

- *Need for an Engineering design of the ICRF antenna*. The ICRH antenna is the least investigated of FIRE's major systems. If the ICRH antenna cannot couple the projected amount of power, then FIRE will fail in its mission. It is recommended that the FIRE team use some available electromagnetic package to determine the likely maximum values of the parallel and perpendicular RF electric fields in the antenna, and compare this with values from current tokamaks like JET that are operating with ELMy H-mode edges.

- *Modeling of particle control and helium exhaust.* Helium exhaust is presently assessed with TSC, assuming a fixed albedo for particles at the plasma boundary. It does not couple the core plasma to the boundary and the divertor. In the divertor, there will be high pressure build-up (with 98% recycling) which will affect the separatrix density due to the short connection length. These two areas need to be coupled; at a minimum, the respective numbers need to be consistent. Viscous flow in the divertor exhaust will contribute even more to high pressure in the divertor. This issue requires neutrals modeling of the exhaust to investigate feasible divertor operation. Also integrated modeling of the edge to see if the required high edge temperatures are consistent with the edge particle control would be helpful.

- *First Wall Heat Load.* The first wall heat loads seem challenging. While a concern in steady-state, this is a greater concern during events like disruption mitigation by large gas-puff. The type I ELMs could also exceed the melting threshold. This should be a topic for future design activity.

What areas need supporting R&D from the base program (experimental, theory, and modeling)?

There are several substantive areas needing broader research, including

- *Investigation of the suppression of neoclassical tearing modes (NTM) by RF current drive.* NTM stabilization by driving currents within the magnetic island has been studied in some detail. However, FIRE may employ lower hybrid waves to modify the broader current density profile (to stabilize NTMs by altering the Δ-prime stability parameter). This technique has not yet been extensively studied in experiment. In addition the feasibility of such current profile control using lower hybrid waves (with adjustment of the $n_{||}$ profile) is not yet in hand. These issues will be a focus of experiments on Alcator C-Mod in the coming years.

- *Development of modified and new diagnostics for burning plasma research.* The success of a burning plasma experiment rests upon our ability to measure plasma behavior. This is a large challenge and includes the study of radiation effects (on conductivity of materials, optical fibers, electromagnetic pulses…), development of new tools such as neutral beams with high current density and spectrometers with high -throughput, the development of new ways to detect alpha particle behavior, and the development of new methods to replace existing diagnostics that are not possible on a burning plasma experiment. Relying on development of exotic neutral beams is a high-risk approach, and alternatives, especially for current density profile and flow measurements, should be carefully considered.

- *Development of an integrated simulation capability applicable to burning plasmas.* Burning plasmas and FIRE in particular have only a limited number of discharges. In order for these limited discharges to be productive scientifically will require consistently achieving specific plasma conditions that are governed by many coupled non-linear interactions. Being able to do this will benefit significantly from an integrated simulation capability able to accurately test all the key non-linear interactions in the presence of strong self heating that results from the fusion process before the experiment is conducted.

- *Investigation of effects of ELMs on tungsten divertor components.* ELMs are life-limiting events for divertor modules in both FIRE and ITER. The tungsten brush design adopted for FIRE is also under consideration for ITER. The effects of pulsed heat loads from ELMs and disruptions can be studied in existing tokamaks (C-Mod is planning extensive tests of the FIRE/ITER tungsten brush design) and simulated in experiments using electron beams to apply controlled heat loads. A related issue is that further investigation of ELM physics and their occurrence in various operating regimes, especially small/no-ELM regimes, can be carried out within the tokamak program.

- *Systematic antenna development.* RF current drive and heating are critical to burning plasma research, and place harsh demands on antennas, particularly arising from an ELMing H-mode edge. This implies the need for a dedicated research program incorporating a systematic approach to antenna development and validation. Tests in tokamaks with high density edge plasma and high neutral pressures are particularly relevant for FIRE.

- *Demonstration of low internal inductance Advanced Operating modes.* The fire AT mode of operation requires operating at a very low internal inductance, whereas experimental data for advanced operating modes is at a higher q, and higher internal inductance. This issue is similar for ITER, and calls for a campaign to determine if these modes of operation can be realized, and what is required to achieve them. Understanding how to achieve these advanced operating modes without an external source of momentum will be important for FIRE AT modes.

- *High Edge Pedestal Temperature*. For successful operation it is believed that FIRE will require a very high edge temperature of 3 to 5 kev. . It should be noted that the edge temperature required for success in FIRE is above what has been achieved in most, if not all, of today's experiments where the transport models have previously been developed and tested. The uncertainty in the possible edge pedestal temperature therefore remains an important unresolved issue for the success of FIRE. More theory, modeling and experiments would be useful in insuring the successful achievement of the needed edge conditions.

Attachment 1

Charge to the Panel of Experts for the Physics Validation Review of FIRE

Using the Technical Assessment at the 2002 Snowmass Summer Study as a starting point, update the assessment of the physics and technical capability of FIRE to address the critical issues in a major Next Step Burning Plasma Experiment. Specifically,

1. Are the mission and objectives identified by FIRE appropriate to answer the critical burning plasma issues in a major next step experiment?

2. Is the proposed physical device sufficiently capable and flexible to answer the critical burning plasma issues proposed in #1? What areas are deficient and what remedies are recommended? What areas need supporting R&D from the base program (experimental, theory and modeling)?

<u>Review Committee Members</u>

Stewart Prager (U of Wisconsin) – Chairman
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