Next Step Options
Program Advisory Committee

To: Dr. Charles Baker, Director
Virtual Laboratory for Technology

Prof. Jeffrey Freidberg, Chair
VLT Program Advisory Committee

From Dr. Tony Taylor, Chair
NSO Program Advisory Committee

Date: March 18, 2003

Date and Place:
The Next Step Options Program Advisory Committee (NSO PAC) met Thursday and Friday, February 27 and February 28, 2003, at General Atomics, in San Diego, California. This was the PAC's fifth meeting (PAC-5).

PAC Members in Attendance:

Dr. Steve Allen	Prof. Tom Jarboe	Dr. Raffi Nazikian
Prof. Cary Forest	Dr. Earl Marmar	Dr. Richard Nygren
Dr. Charles Greenfield	Dr. T. K. Mau	Dr. Dave Petti
Dr. Wayne Houlberg	Prof. Gerald Navratil	Dr. Tony Taylor

PAC Members not in Attendance
Dr. David Gates, Dr. Paul Thomas, and Dr. Mitsuru Kikuchi

We issued an interim report on Friday, February 28, 2003 that addressed item 3 and item 4 of the charge. These will appear first in this report, with no change. Items 1 and 2 of the charge will follow.

<u>Charge 3:</u>

Given the likelihood of very limited fusion funding in FY 2004, what is the best approach for following the FESAC recommendations for maintaining the viability of a FIRE option as the ITER negotiations are pursued?

Recommendation 3: We strongly encourage developing a process for community-wide support and involvement in a national burning plasma effort. This process should be constructed to maintain the community consensus and program balance expressed at the 2002 Fusion Energy Science Summer Study at Snowmass and the FESAC/Austin report on a "Burning Plasma Program Strategy to Advance Fusion Energy,'' September 2002. The long-range goal of this effort should be to develop a national framework to most effectively use our limited resources in advancing a burning plasma experiment, either ITER or FIRE, in accordance with the strategy recommended in the FESAC/Austin Burning Plasma report. This recommendation reiterates a recommendation we made in the NSO PAC-3 report: "*We strongly encourage developing a process for community support and involvement in a burning plasma experiment. We recommend a more definitive proposal be developed as a basis for discussion and strongly support presenting the proposal to the larger community for discussion.*"

The FESAC/Austin Burning Plasma strategy is to continue work on FIRE to allow initiation of a conceptual design project on FIRE if ITER does not go forward on terms acceptable to the US. After FIRE completes a PVR at the end of FY03, work on FIRE must continue until an ITER decision is made (expected in FY04) to follow the FESAC/Austin BP strategy. At a minimum, for FIRE to remain a viable project and a credible element in the FESAC/Austin BP strategy, progress must continue on key open issues identified at the PVR together with conceptual design preparation work. Continuing this post-PVR work on FIRE with a team of specialists capable of starting work on a FIRE conceptual design when needed is an essential element of maintaining FIRE as a viable BP option for the US. If the US fusion program is organized to pursue burning plasma experiment design and planning in a team that has dual responsibility for advancing both ITER and FIRE, it will be possible to maintain FIRE in the FESAC/Austin strategy while also carrying out essential work in support of the ITER negotiations.

While the specific charge to the NSO PAC deals with progress of FIRE as the ITER negotiations are pursued, the PAC feels compelled to make a broader statement with regard to an overall strategy for a burning plasma experiment.

The recent decision to join ITER negotiations brings an immediate need not only to muster technical support to address cost estimates for ITER but also to provide mechanisms through which the community can gain information about ITER and provide input on preferences and capabilities for areas of work. We feel this is a necessary continuation of the Snowmass process and is important to keep the community informed about and aligned with the decisions that will be considered as negotiations proceed. Specifically, we recommend that a broad-based and open national structure or leadership team be formed expeditiously to participate with OFES in decision-making regarding the US burning plasma program. Furthermore, the US ITER and FIRE efforts should be brought together within this structure. In the immediate future, outreach efforts, such as workshops, should be organized to encourage and expand the community involvement in the process and mobilize the needed technical support.

<u>Charge 4:</u>

Should the vision for FIRE focus more strongly on AT? If so, what would be an attractive goal?

Recommendation 4: The primary mission for FIRE is to be a vehicle for studying the physics of burning plasmas. In order to maximize the probability that FIRE will be able to deliver the alpha-dominated conditions required to meet this mission, the capability for H-Mode operation at B=10T with Q~10, should be maintained in the design. AT operation, at lower field (B~6 T), with Q~5, will explore very important physics and technology, with the long-term aim of improving the tokamak as a fusion reactor; the development and assessment of options and requirements for AT operation on FIRE should continue. At the same time, the higher field capabilities should not be compromised.

<u>Charge 1:</u>

Has the FIRE team addressed the critical technical issues identified by the NSO PAC and Snowmass?

The FIRE team did an excellent job with limited resources in addressing the issues the PAC identified, especially those deemed high priorities for the Snowmass summer study. They also were active participants in the preparation for Snowmass and the Snowmass meeting. We commend them for their hard work.

Although progress was made on many of the items, there is still work to be done on a number of them in preparation for the Physics Validation Review (PVR). We address a number of these below. The second digit in the heading refers to the number designation in the PAC-4 report.

1.1 NBI for FIRE:

Finding 1.1, Response to Recommendation 1: We recommended that the FIRE Team explore the possibility adding tangential access for NBI. Analysis showed that effective central heating with NBI required ~1 MeV energies. Given the development needed for such NBI energy, the tangential access design change was not pursued in favor of ICRF. However, for study of AT modes in FIRE, the density is only about half the high field levels, so the FIRE Team proposes to re-examine the NBI option for presentation at the PVR.

Recommendation 1.1: We concur, and recommend that the requirements for driving edge rotation at 2% of the Alfvén speed in AT plasmas also be established.

1.2 DND Vs SND

Finding 1.2, Response to Recommendation 2: The FIRE design team has selected a double-null divertor (DND) configuration over the single-null divertor (SND). Some progress has been made since last year in documenting the reasons

for this decision. A number of modeling studies have shown that the MHD stability limit increases with triangularity. The FIRE team has shown data from the ITPA database illustrating higher margin in confinement and higher margin in the operating density wrt the Greenwald limit, with increasing triangularity. These all favor the DND choice, since triangularity > ~ 0.5 requires a DND. Most of the detailed work is completed, but documentation and clear articulation remain.
Recommendation 1.2: The FIRE team should better articulate the choice of DND for the PVR, including the specific gain expected for FIRE. The FIRE team should remain involved in the experimental and numerical studies on the impact of stronger shaping in support of the DIII-D and Alcator C-Mod AT programs.

1.3 Nuclear Heating of VV

Finding 1.3, Response to recommendation 3: The PAC previously noted that the pulse lengths for high performance AT plasma scenarios in FIRE are expected to be limited by nuclear heating of the vacuum vessel. The increase in size from R = 2.0 m to R = 2.14 m and from a = 0.525 m to a = 0.595, and the decrease of nominal fusion power from 200 MW to 150 MW reduces the nuclear heating by 38 %. Increasing the thickness of the PFC tiles is also beneficial. However, the FIRE team did not clarify if the limit on pulse duration remains nuclear heating or not.
Recommendation 1.3: The project should clarify the limitations on the pulse length of high performance AT plasmas, and consider whether vessel design changes could be accommodated in order to reduce these stresses, so that the pulse length could be lengthened to match the TF-coil heating limits.

1.4 Auxiliary Heating/Current Drive Systems

Finding 1.4, Response to Recommendation 4: The PAC finds that the FIRE team has made progress in the area of auxiliary heating and current drive systems, although much remains to be done before the PVR. In particular, the lower hybrid current drive system needs considerable attention. Several technical areas need addressing in the near term: availability of high power klystroms at the appropriate frequency (5 GHz), Coupling of LHCD to H-mode plasmas, and the power handling capabilities of the antennas.
Recommendation 1.4: The project should discuss with industry (CPI or Thomson/Thales, etc.) to insure a path for tube development. Ongoing experiments should be reviewed, full wave modeling completed, and FIRE relevant R&D should be completed to improve confidence in coupling. The power handling capabilities of the antenna for long pulses should be analyzed.

1.5 Off-normal Events (Management of Disruptions and ELMs)

Finding1.5, Response to recommendation 5: For high power tokamaks, the issues of localized heat loads on PFCs and large forces caused by electrical currents generated during disruptions as well as heat loads from ELMs are well-recognized and are critical issues for PFCs in FIRE. The issue of local electro-mechanical forces was raised as a critical issue at Snowmass. The PAC recognizes that ongoing work on ELM heat loads and planned work on disruptions can at least partially address these issues for FIRE. Off-normal events during operation of FIRE may be expected at some point during operation to cause melting of the tips of some tungsten rods.

Recommendation 1.5: In preparation for the PVR, the FIRE team: a) demonstrate the survivability of a limited number of unmitigated disruptions from the expected worse case disruption loads; b) show that a combination of disruption mitigation techniques (e.g., rapid gas puffing) and robustness against erosion and electromagnetic loads can be expected to provide a satisfactory lifetime for PFCs; and c) show that assumptions about the power and frequency of ELMs are reasonable for FIRE plasmas. The consequence of melted rods and the provisions for repair if needed should also be addressed.

1.6 Confinement Scaling Studies

Finding 1.6.1, Response to recommendation 6.1: The robustness of the projected operating point to variations in scaling relations was studied extensively under two Snowmass working groups, WG-P4 and WG-E2. That work should serve as a sound basis for preparation for the PVR.

Finding1.6.2, Response to Recommendation 6.2: Several theory-based modeling efforts addressed the incorporation of pedestal physics in FIRE projections for the Snowmass studies. This is recognized as a longer-range effort that the community is continuing to address.

Recommendation 1.6: The FIRE Team should be prepared to update performance projections for the PVR, if there is a significant update of pedestal predictions.

1.7 AT Physics

Finding 1.7.1, Response to recommendation 7.1: The Snowmass study found that FIRE is designed with sufficient flexibility to carry out an extensive AT research program. New calculations have expanded the available operating space for AT regimes in FIRE, with Q = 5-10, β_N = 2.5-4.5, f_{BS} = 50-90%+ and τ_{flat}/τ_{skin} = 1-5 now being accessible (although not simultaneously).

Recommendation 1.7.1: Calculations should continue to pursue predictions of AT performance in FIRE. These should take advantage of continuing progress in development of physics models for transport, heating, current drive and stability. The team should seek useful input to these studies from experimental results in present-day devices, in particular Alcator C-Mod and DIII–D.

Finding 1.7.2, Response to recommendation 7.1: These AT scenario calculations make some questionable assumptions, in particular that radiative divertor solutions are available for low density plasmas with 50-100% of the power radiated. Such solutions do not currently exist, but will be an issue for any next-step device pursuing AT scenarios.

Recommendation 1.7.2: The FIRE team should continue to engage the divertor community to develop divertor solutions for handling high power exhausted from a low density AT plasma.

Finding 1.7.3, Response to Recommendation 7.2: Although the outlook for diagnostics in a burning plasma experiment was improved by the Snowmass effort, we continue to be concerned about the lack of progress in identification of AT specific diagnostics.

Recommendation1.7.3: We reiterate Recommendation 7.2 from the PAC-4 report. More effort is required to identify viable diagnostic concepts for detailed current and pressure profile measurements in AT regimes.

1.8 Engage the Divertor Physics Community

Finding 1.8, Response to Recommendation 8: We recommended that the FIRE Team engage the US divertor community in assessing and contributing to the FIRE divertor design by sponsoring a short workshop. While the press of time preparing for Snowmass did not permit this to occur, participation in Snowmass accomplished much of the intent of our recommendation.

Recommendation 1.8: We encourage continuation of the work with the C-Mod and DIII-D divertor groups to propose FIRE relevant experiments.

1.9 Physics validation Review: Schedule:

Finding1.9, Response to recommendation 9: The work by the FIRE Team preparing for and the community assessment at Snowmass 2002 has led to a reasonably complete pre-conceptual design.

Recommendation 1.9: We recommend that the FIRE Team prepare for a Physics Validation Review to be scheduled with the DOE OFES for September 2003.

1.12 Other Physics Action Items:

Finding 1.12.1, Response to Recommendation 12.1: The FIRE team in collaboration with the Snowmass WG-P2 considered the interaction of RF waves with alpha particles. The result of the study was that if the alpha particles remained core localized then the coupling with RF waves would not be a problem to PFCs or to core FW heating efficiency. Consideration was given to AT scenarios. It was found that the effect of magnetic ripple would merely lower the population of alpha particles in the core, not broaden the alpha distribution. The unconfined alphas could not effectively interact with the RF waves. Hence no overall negative impact is expected because of coupling between RF waves and alpha particles in normal or AT regimes.

Finding1.12.2, Response to Recommendation 12.2: The goal of constructing popcon plots for alpha driven instabilities was to identify a parameter regime (not necessarily at high Q) where dominant alpha particle effects could be observed in a reactor relevant regime. The Snowmass summer study addressed the issue of the excitation of Alfven modes in conventional positive shear and reverse magnetic shear configurations in the three burning plasma proposals FIRE, IGNITOR and

ITER. Popcons were produced in collaboration with the FIRE team and the Snowmass WG-P2 group showing that the alpha particle drive was comparable to ion Landau damping at the nominal FIRE H-mode operating point. However, more detailed analysis, taking into account radiative damping and collisional damping, revealed that FIRE was well in the stable regime for either positive or reverse magnetic shear regimes. The crucial parameter for the excitation of Alfven eigenmodes was found to be plasma temperature. The conclusion of the study was that FIRE needs to access a range of temperatures roughly a factor of two above the nominal H-mode operating point in order to observe the excitation of Alven eigenmodes relevant to ARIES parameters. Operation at these high temperatures requires operation at lower density and there is concern about the divertor compatibility at the lower density.
Recommendation1.12: More detailed analysis of the FIRE AT regime should be performed in the future with advanced non-perturbative stability codes in order to refine and strengthen the conclusions of the Snowmass summer study.

1.13 Range of Operational Space
Finding1.13, Response to Recommendation 13: Good progress was reported at Snowmass in characterizing the ranges of physics parameters accessible for various major physics studies.
Recommendation 1.13: Because this will be a critical contribution to the success of the PVR, it needs to be summarized clearly and should be related to the needs of ARIES.

1.14 Roadmaps with FIRE:
Finding, Response to Recommendation 14: We recommended that the FIRE Team define a fusion development "roadmap" and present this at Snowmass. This was completed very effectively as part of the E4 Development Path working group. The fusion development strategies which emerged from Snowmass have been adopted by FESAC/Austin BP Strategy and were also presented to the NAS Burning Plasma Review Panel.

Charge 2:

What technical issues need increased attention in preparation for the PVR? Which issues should be lower priority?

In answering this charge, we discussed a number of important physics issues that remain. The following list (not in priority order) requires some specific attention prior to physics validation review (PVR). A number of these issues are the same as those articulated in response to Charge 1, and will be so indicated.

2.1 Resolution of mechanical loads during disruptions : Please see 1.5 and recommendation 1.5 above.

2.2 Melting of Tungsten during disruptions and ELMs: Please see item 1.5 recommendation 1.5 above.

2.3 Ability to Defend Choice of DND vs SND: Please see item 1.2 recommendation 1.2 above.

2.4 **Articulate high density divertor solution distinct from AT divertor :**
Finding 2.4: FIRE has two overall operating modes: Phase I, with a burning plasma focus, and Phase II, with an increased emphasis on Advanced Tokamak physics. In Phase I, the FIRE designs show that the edge density is high enough that a radiative divertor solution similar to that envisioned for ITER is probably appropriate; with the issues of a more compact divertor and the use of Tungsten. The physics basis for Phase II, in which the edge and divertor density is lower, will probably require a new physics basis, currently being developed in experiments, with enhanced impurity radiation in the divertor. One model of this operation involves induced SOL plasma flow with deuterium puffing and pumping; FIRE has the basic capabilities for this mode, and should pursue the coupling of these plasmas with the core plasma models.
Recommendation 2.4.1: In both cases, the plasma shape is DN, or close to DN, which has effects on up/down power and particle exhaust, ELMs, and the H-mode power threshold. This needs to be integrated into the overall control and operational scenarios.
Recommendation 2.4.2: The detailed physics basis for power and particle control is different for each of these two phases and should be presented clearly.

2.5 Develop Firmer Physics Basis for LHCD: Please see item 1.4 and recommendation 1.4 above.

2.6 Evaluate possible FIRE regimes for the study of TAE modes: Please see item 1.8 and recommendation 1.8 above

2.7 Integration of diagnostics: Please see item 1.7 and recommendation 1.7.3 above.