Summary of FIRE Actions in Response to Next Step Options Program Advisory Committee Report #4, January 2002

Previous Findings and Recommendations

The FIRE Project has made good progress on responding to many of the recommendations that we have given in our previous reports. However, there remain a number of issues not yet addressed. These issues remain important, but we will not reiterate them below except where we deem they are of very high priority.

1. NBI for FIRE

Finding 1: At our previous meeting we reported in Finding 9.0 that recent tokamak experiments have shown the importance of plasma rotation, driven by tangentially injected neutral beams, on MHD mode control and that the incorporation of tangential access in the FIRE design could benefit several important diagnostic techniques. Where direct comparisons have been made (e.g. on JET) ICRF is found to be just as effective as beams for plasma heating. Nevertheless, since relatively little of the high performance data in the world tokamak data base comes from purely RF heated plasmas, the reliance of FIRE on only RF heating increases the extrapolation from present experiments and hence the level of uncertainty in the extrapolation.

Recommendation 1: When the FIRE team works with the Snowmass Working Groups to prepare for the Snowmass 2002 meeting, the possibility of adding tangential access to the design, and using NBI as part of the baseline (or upgrade) heating set on FIRE should be included to strengthen its case to the community.

Action 1: For the conventional H-Mode: The beam energy required for 50% of the power to be deposited inside a/2 for quasi-tangential injection (R_{tan} = 0.75m) is ~ 1 MeV. Since 1 MeV beams would require an extensive development program this approach was abandoned in favor of ICRF. The edge plasma rotation induced by quasi-tangential injection of 120 keV neutral beams was calculated and presented at Snowmass. Specifically the edge plasma rotation was well below the 2% v_{Alfven} thought to be needed for RWM stabilization. However, the edge flow shear was of interest as a possible transport control technique. The use of an intense 150 keV/amu beam for beam diagnostics would yield useful measurements into the core region. **For the AT mode:** the beam deposition is much improved due to ~50% density reduction. This will be quantified for the PVR.

2. DND vs. SND

Finding 2: The FIRE design team has selected a double-null divertor configuration, but has not documented) why it made this decision. Because FIRE is unique in this respect compared to the other proposed Next-Step devices (ITER and IGNITOR) and because this adds cost and complexity to the device, we believe that the project will be asked at Snowmass to explain the reasons for making this design choice.

Recommendation 2: Prior to Snowmass, the FIRE team should articulate the physics basis for choosing a double-null divertor configuration.

Action 2: The primary reason for choosing the DN was that it provides the highest triangularity which in turn is beneficial for confinement in the H-mode, and would be expected to lead to higher betas. Recent data from ASDEX Upgrade, JT-60U and DIII-D have indicated that near

DN or DN configurations provide the additional benefit of smaller ELMs. This topic was discussed at Snowmass and IAEA at Lyon. FIRE has proposed SN-DN comparison experiments on both C-Mod and DIII-D. FIRE plans to initiate a more thorough and comprehensive study of DN vs SN as part of a proposed US Burning Plasma Initiative. **Need SN/DN comparisons in existing experiments for candidate burning plasma AT modes. More on this issue for PVR.**

3. <u>Nuclear heating of VV</u>

Finding 3: The pulse lengths for high performance AT plasma scenarios in FIRE are expected to be limited by nuclear heating of the vacuum vessel. Depending on the precise scenario models, pulse-length to skin-time ratios in the range from 1.3 to 2.8 are expected. Since the limit is due to the stresses, which result from differential expansion, it might be possible to extend the pulse length through modification of the double-walled vessel design.
Recommendation 3: The project should 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.
Action 3: Three things are being done in this area: 1) the machine configuration changes endorsed at the last PAC meeting (R = 2.0m to 2.14m, a = 0.525m to 0.595m and nominal fusion power from 200MW to 150MW has reduced the nuclear heating by 38%. Also 2): the thickness of the PFC tiles has been increased to ~5 cm to provide more thermal inertia and neutron shielding, and 3) the outer shell of the double layer vacuum vessel could be preheated to reduced the stresses induced by nuclear heating. These positive effects were not fully taken credit for at the Snowmass Assessment.

4. <u>Auxiliary Heating/Current Drive Systems</u>

Finding 4: The design of the auxiliary heating systems, ICRH for high-Q experiments and LHCD for AT experiments, lags the other conceptual design efforts. A credible design of the auxiliary heating/current drive systems in regard to both power density and plasma facing components is critical to a realistic assessment of FIRE.
Recommendation 4: A more detailed design of the auxiliary heating/CD systems, subject to an expert review, needs to be done before Snowmass.
Action 4: A preconceptual design for the ICRF launchers was presented at Snowmass by D. Swain. A preconceptual design of the Lower Hybrid Launcher is planned for the PVR. P. Bonoli in collaboration with R. Harvey) have been updating the Lower Hybrid CD drive calculations for FIRE and ITER. These reduced effciencies were used in the FIRE calculations presented at Snowmass. This is being followed up by the ITPA. The detailed aspects of the plasma interface with the LH and ICRF launcher remains to be done. As a result of suggestions at Snowmass, FIRE is examining the feasibility of ECCD for current profile control in ATs.

5. <u>Off-normal events</u>

Finding 5: Off-normal events, including disruptions, VDEs and ELMs, can result in substantial localized energy deposition and electromagnetic loads on plasma facing components. The magnitude and frequency of such events would directly impact the thermo-mechanical performance and erosion lifetime of these components.
Recommendation 5: It is recommended that a table be developed to characterize off-normal events for FIRE and the corresponding design requirements on the PFCs. For each off-normal

event, this table should include location, frequency, energy, time scale, and affected area. The corresponding temperature, thermal stress, and erosion associated with these events should be analyzed in the future.
Action 5: Similar tables were prepared by Group E3 at Snowmass. This area continues to be a critical area for FIRE as well as any burning plasma experiment. Techniques to mitigate the effects of ELMs such as DN, rapid pellet injection need continued testing and analysis. In addition, the disruption mitigation techniques such as gas jets being developed on DIII-D, and improved feedback control systems being developed on ASDEX-U are promising for FIRE. This area is a major problem area for FIRE as it is for ARIES.

6. Confinement Scaling Studies

Finding 6.1: We find that good progress has been made in incorporating results of non-dimensional scaling experiments into the design projections and optimization. Some progress also has been made into looking at how robust is the projected operating point is to variations in the choice of scaling relations.
Recommendation 6.1: We recommend that the project complete their proposed work on non-dimensional scaling (i.e., Q vs. H for Electrostatic GyroBohm). Work should be continued on the sensitivity of various confinement scaling relations to the FIRE operating point and to FIRE's choice of triangularity, double null, high edge density, etc.
Action 6.1: This was extensively studied at Snowmass by both WG-P4 and WG-E2.

Finding 6.2: We find that good progress has been made in using theory-based transport modeling for the AT scenario development. However, pedestal physics have yet to be included in the theory-based modeling, necessitating a normalization of the transport to a global scaling relation.
Recommendation 6.2: We recommend that the project work to incorporate pedestal physics into the theory-based modeling, possibly in consultation with the ITPA, and eliminate the normalization to global scaling relations.
This should be viewed as a longer-range effort and only preliminary results are expected prior to Snowmass.
Action 6.2: Good progress was made in this area by the community at Snowmass. This area continues as a major need in the development of a self-consistent transport model. The recently released (Feb 18, 2003) update to GLF23 has been incorporated into the TSC calculations for FIRE. The previous results for H-mode have been reproduced within a few %, calculations for reversed shear AT cases are underway.

7. AT physics

Finding 7: The FIRE team presented an initial analysis of accessibility to an advanced tokamak operation regime using the base facility, plus some additional tools specific to exploring AT physics in a burning plasma environment. The target AT regime is characterized by $n(0)/\langle n\rangle > 1.5$, $P(0)/\langle P\rangle = 2.5 - 4.0$, $H > 1.2$, $0.6 < n/n_G < 0.95$, and $1.3 < \tau_{pulse}\tau_{skin} < 2.8$. The committee endorses this target parameter regime for exploration of AT physics in FIRE.
Recommendation 7.1: The FIRE team should better define the flexibility needed in profile control for AT regime studies. This includes the requirements and capabilities for current profile and pressure profile modifications.

Action 7.1: An extensive systems study was done by WG E2 at Snowmass and later updated for the IAEA meeting. Optimization of the power handling extended the Q = 5 operating range to $\beta_N \sim 4$, $f_{bs} \sim 80\%$ for up to 5 skin times.

Recommendation 7.2: More effort is required to identify viable diagnostic concepts for detailed current and pressure profile measurements in AT regimes. (presumably done in concert with and support from the Snowmass working groups)
Action 7.2: This is ongoing. We must find a way to muster the resources to drive development in this area for burning plasmas in general.

8. <u>Engage the divertor physics community</u>
Finding 8: The FIRE divertor design operates at significantly higher heat flux than present-day tokamaks and has pulse lengths, that force the use of actively cooled surfaces. In addition, the design requires that the divertor provide helium ash removal and sufficient pumping to produce peaked density profiles [n(0)/<n> > 1.5] in low-density AT plasmas. Further unique features of the FIRE divertor include a double-null configuration, the use of high-Z targets, and an inertially cooled private region baffle. Because the ITER project has focused international attention on the divertor and devoted considerable resources to its divertor design, the FIRE team undoubtedly will be asked to show how its divertor design will allow the device to accomplish its mission. So far, the project has focused more on the technology of its solution rather than its physics.
Recommendation 8: The project should engage the US divertor physics community to validate and improve the articulation of the physics basis for its design choices. The experience of the DIII-D divertor group with double-null pumped divertor operation in AT plasmas should be particularly valuable, as would be the high-field RF-heated experience of the C-Mod team. We recommend that the project sponsor a short workshop on divertor physics as the best way to engage the community on this subject.
Action 8: This is an excellent idea. However, the press of time last year made this too difficult to implement formally. Good progress was made at Snowmass to get people from the divertor engaged. Some progress has been made with proposals for experiments on C-Mod and DIII-D. We need a more formal US Burning Plasma Physics structure and allocated resources to do this.

9. <u>Physics Validation Review: Schedule</u>
Finding 9: Completion of the uniform technical assessment of FIRE as part of the preparation for and discussions at Snowmass 2002, should result in a reasonably complete pre-conceptual design of FIRE. This will also position the FIRE project to complete a DOE Physics Validation Review following the conclusion of the Snowmass meeting.
Response 9: FIRE has proposed a Physics Validation Review for September ,2003.

FIRE PROJECT PREPARATION FOR SNOWMASS
10. <u>Continuing FIRE Effort</u>
Finding 10: We are please to note that NSO effort on the FIRE project was maintained at a nearly level effort (FY 2002 wrt FY 2001) and that additional resources were provided by DOE for the NSO uniform technical assessment in preparation for Snowmass.

11. <u>Maturity of Physics Program in Comparison with the Facility</u>

Finding 11: Much of the FIRE work so far has, of necessity, been concerned with design of the facility. In comparison, the articulation of the planned physics program is less mature. This imbalance is reflected in the list of twelve FIRE action items in preparation for Snowmass, only one of which is concerned with physics issues. However, scientific goals and assessment will be important at Snowmass (note that the physics working groups are slated to receive 75% of the NSO Snowmass funding). Furthermore, the view of FIRE by the community will depend on its perceived ability and operational flexibility as an instrument for doing science.
Recommendation 11.1: FIRE should begin to outline an operational plan for its physics program (6 years, 500 full-power shots per year).
Action 11.1: A simplified operational plan was developed for FIRE and presented at Snowmass, IAEA and APS-DPP.

Recommendation 11.2: FIRE should articulate what types of physics could be done on this facility, relative to other next step burning plasma facilities, highlighting the use of the facility as a scientific instrument. This work should be carried out with the cooperation of the uniform technical assessment effort.
Action 11.2: Good progress made at Snowmass and with the NRC panel on Burning Plasma assessment.

Recommendation 11.3: The NSO PAC recommends that the FIRE group become proactive in the Snowmass process. The Snowmass organizing committee should identify, in particular, specific project people to work with each of the Snowmass sub-groups.
Action 11.3: The FIRE group was very active at Snowmass, and benefited from the constructive support of the community.

12. <u>Other Physics Action Items for FIRE:</u>
Recommendation 12.1 In preparation for Snowmass, consider the interaction of RF with alpha particles.
Action 12.1: This was considered by the WG P4.
Recommendation 12. 2 Construct popcon diagrams with more detailed alpha particle stability input.
Action 12.2: PopCon like plots were produced in collaboration with WG-P2 showing that FIRE's nominal H-Mode operating point was situated right on the TAE instability boundary while ITER was well into the unstable region, and IGNITOR was well into the stable region. Additional work needs to be done for AT regimes.

13. <u>Range of Operational Space</u>
Finding 13: The extent of the operating space is not sufficiently characterized in relation to the range of parameters required to carry out the physics program.
Recommendation 13: For each major physics issue relevant to the mission of the experiment, the relevant physics parameters should be identified and the range of parameters accessible to the experiment should be discussed. This work should be carried out in conjunction with the "uniform assessment" activity for Snowmass.
Action 13.1: Parts were done at Snowmass, needs to be summarized for PVR, also should be connected to the needs of ARIES.

14 <u>Roadmaps with FIRE</u>

Finding 14: The realization of fusion energy will require significant advances in burning plasma science and related technologies. An important discriminator among the various approaches to burning plasma experiments is the flexibility to examine these challenges and to define a fusion development path or "roadmap". The FIRE project has made a good start at articulating a development path with FIRE as one of the central elements.

Recommendation 14: In preparation for the Snowmass activity, FIRE should propose a fusion development path consistent with its expected performance and scientific/technology mission. The development path should include its role in addressing the key fusion science/technology issues, a brief overview of its base experimental program, what follow-on or complementary experiments are required, and a brief summary of advantages and disadvantages of a multi-machine vs. a single-step to demo development strategy.

Action 14: At Snowmass FIRE was active in the Development Path WG-E4. The E4 report Section 4.3 describes the FIRE Based development path. FIRE also presented a comprehensive comparison of the FIRE-Based and ITER-Based Development paths to the FESAC Development Path Panel. G. Navratil also presented a comparison to the NRC Panel January 17, 2003.

NSO PLANS FOR UNIFORM TECHNICAL ASSESSMENT

15. <u>Support for Students and University Researchers</u>

Finding 15: The committee notes that the initial allocation of Snowmass-specific resources supports mainly individuals in the national labs. It is also important to encourage the widest possible community attendance, including younger community members such as senior graduate students and early-career scientists based in academic institutions. Some funding has been set aside to support attendance of university-based fusion researchers.

Recommendation 15: Support for travel to all relevant Snowmass-related activities (including preparatory meetings as well as Snowmass itself) should be made available for early career scientists, post-docs, and senior graduate students.

Action 15: Some funds were made available by DOE for Snowmass support.

16. <u>International participation</u>

Finding 16: The PAC recognizes that in certain instances experts from overseas are necessary in order to perform critical tasks in the physics assessment of the burning plasma options. The PAC further recognizes that the participation of these key individuals will be unlikely without some token level of support in the form of travel funds.

Action 16: There was strong international participation at Snowmass with the exception of the Japanese.