FIRE Actions in Response to Next Step Options Program Advisory Committee Report

NSO-PAC CHARGES #1 & #2 RELATED TO BURNING PLASMA

The chairman reminded the PAC that at its previous meetings, it had decided that these two charges are long-range tasks and therefore would be addressed in subsequent PAC meetings, following the reception of input from the Workshop on Burning Plasma Science. The PAC had adopted a proposal to establish a an NSO-PAC subgroup consisting of Jerry Navratil, Raffi Nazikian, and Jim Van Dam, who would merge the outputs of the Workshops and circulate a draft to the NSO –PAC members for comment. The chairman will take responsibility for insuring this activity is completed prior to the next PAC meeting.

1. Broader Community Activities and Community Governance

Gerry Navratil, discussed the University Fusion Associates sponsored workshops on burning plasmas and discussed the plans for a 2002 Snowmass Summer Study on the topic of burning plasmas. Stewart Prager presented some points for discussion on a burning plasma collaboratory as a mechanism for supporting burning plasma studies, facilitating national discussion and participation in burning plasmas, and helping prepare for the Snowmass Summer Study. The collaboratory would also be an advocate for burning plasma studies and burning plasma experiments. In the near term, the collaboratory would resemble a working group or study group, for example like the TTF. In the longer term, when a burning plasma experiment was funded, the collaboratory might transition into a consortium (a legal entity) that could construct and carry out a burning plasma experiment.

Finding 1.1: We find that expanded NSO resources will be needed to carry out the support activities in preparation for the Snowmass Summer Study. The present level of effort in physics analysis is not fully adequate for ongoing high priority FIRE studies, and preparing for and participating in the uniform technical studies of the three options as called for by the FESAC Panel will overextend NSO resources.
Finding 1.2: The community needs to try a new tactic to support burning plasma activities. We find the collaboratory is a good approach for community participation in a burning plasma effort, and that a collaboratory would have a positive impact on NSO activities and other burning plasma efforts in the near term.

Recommendation 1.1 It is important to maintain a strong focused effort on the FIRE physics and engineering studies. High priority must also be given to efforts on gathering information on the three burning plasma options in preparation and execution of the Snowmass uniform technical studies.

Action 1.1: FIRE will use its FY 02 resources to address critical issues in preparation for the Snowmass Assessment. FIRE will also update the key sections of the FIRE Engineering Report to incorporate the baseline design point of R= 7.7 MA, 10T at R = 2.14m and A = 3.6. Detailed drawings will not be updated where there are no technical issues. FIRE has setup a Snowmass preparation web site with detailed information on FIRE, ITER and IGNITOR.

Recommendation 1.2 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.

Action 1.2: The Burning Plasma Collaboratory Proposal has been deferred since the activities identified for the early stages would overlap with the Snowmass Uniform Assessment Activities. An active FIRE Outreach activity is being continued, that includes discussion on siting possibilities and development path strategies. An evening Town meeting at the APS-DPP and the Burning Plasma Tutorial and Fast Particle Physics invited talk were a good start at involving the broader plasma physics community. The recent Snowmass organization meeting discussed this issue and is working to integrate Community issues into the program.

NSO-PAC CHARGES #3 & #4 RELATED TO FIRE

The PAC heard several presentations concerning the FIRE pre-conceptual design effort and its recent progress. We note excellent progress in a number of areas and commend the project on the effort made with resources available. We note that it is easy for the PAC to develop far more compelling recommendations than the project has resources to complete, and recognize some indication of priority is called for. We have divided our comments into two groups with topics 1 – 6 in the first group being of higher priority than the second grouping of topics 7 – 13. The PAC offers the following comments.

2. Science Objectives

Progress on the Vision Statement, Mission Statement, and Scientific Objectives were presented. More work is still needed to integrate these and to explain their implications for the FIRE design more clearly. The PAC will assist this effort by assembling responses to Charges 1 and 2 from summaries of the two Burning Plasma Workshops. Finding 3.1 acknowledges progress by the FIRE Design Team, while Findings 3.2-3.3 are reiterations of Findings 2.1-2.2 from the PAC-2 Report. Recommendations 3.1-3.3 are reiterations of Recommendations 2.1-2.3 of the PAC-2 Report.

Finding 2.1: The added scientific objective to ‘explore and understand the strong non-linear coupling that is fundamental to fusion-dominated plasma behavior’ is a good first step, but the set of objectives still needs considerably more work.

Finding 2.2*:* We endorse the logical structure presented by the project for constructing its mission statement. However, the mission statement still lacks excitement and a sense of compelling scientific need.
Finding 2.3*:* Also, as a major DOE scientific facility (if built), FIRE should have a broad scientific mission.

Recommendation 2.1: Establish the proposed ad hoc working group that will flesh out the overall mission statement and report their progress at the next NSO-PAC meeting. Also, examine more mission statements of other federally funded research projects (as recommended in the PAC-1 report).

Action 2.1: Not yet. Many discussions held with people outside fusion where interest is high. Interest within the fusion community is quite high, but people are very busy with their "own program." We need to get people to consider this as their own program, their future. "FIRE, the Movie" a visualization of a burning plasma phenomena that will stimulate interest inside and outside the fusion community is needed. (see Action 2.2)

Recommendation 2.2*:* In the list of scientific objectives, put more emphasis on the strong nonlinear coupling of physics phenomena (e.g., bootstrap current, MHD stability, confinement, alpha effects, boundary behavior, etc.) that will occur in a burning plasma.

Action 2.2: This emphasis is being made at the general level. A simulation of these effects with good visualization is needed. Discussions have been held trying to stimulate interest in a comprehensive simulation. During the proposal / design phase, this virtual burning plasma would be useful to illustrate the physics issues and excitement and provide guidance for the design. During the operational phase, the simulation would guide the experiment and would be benchmarked and updated by experimental results. Upon completion of the experiment the Virtual Burning Plasma simulation would be the legacy code to carry the scientific information forward to other configurations and to future experiments. Perhaps, this simulation activity will attain a critical mass during the Snowmass Preparation activity.

Recommendation 2.3: Open up the list of scientific objectives to the possibility of including non-fusion research.

Action 2.3: The door is open for ideas and proposals for non-fusion science proposals in eg, astrophysics. However, this is not viewed as the driver for defining and justifying the experiment.

3. Confinement scaling

Finding 3.1: We endorse the use of the widely accepted ITER98(y,2) database for making projections, especially for the sake of communicating with the broader fusion community. We are concerned, however, that some physics may be missing in this

scaling, which leads to disagreement with dimensionless scaling results (e.g., steeper decline with power and beta) in individual experiments.
Finding 3.2: We find that good progress has been made in exploring the implications of confinement scaling and in using theory-based modeling, but more work is needed. The project should not base the design on a single confinement scaling relation. More extensive comparisons to existing databases and scaling relations are required.
Finding 3.3: We acknowledge that the project has documented its choice of H(y,2)=1.1 in various publications, but the physics is not yet compelling. More work is needed to support the choice of H(y,2)=1.1.

Recommendation 3.1: We recommend that the project consider the impact of incorporating results of non-dimensional scaling experiments into their design projections, which may lead to different optimizations. For example, the project should explore the impact of electrostatic, gyro-Bohm-like transport scaling on the projected operating space as well as on the device optimization.

Action 3.1

1. Aspect ratio optimization using EGB. Done - Jardin
2. PopCon Plot with EGB. Done - Mandrekas
3. Q vs H for EGB Meade to be done
4. Non-dimensional scaling experiments are being discussed with DIII-D and C-Mod. Also possible ITPA discussion item.

Recommendation 3.2(a): We recommend that he project look at how robust the projected operating point is to variations in the choice of scaling relations, and how the device optimization may change.

1. H(y,2) vs n/n_{GW} for the new H-Mode data base – Cordey/Knudsen/DeBoo
2. $q^2 R \nabla \beta \alpha$ on Pop Con or performance Curves. Done -Mandrekas
3. Triangularity, double null, all metal, high edge density effects need evaluation,
4. FIRE Mission insensitive to small changes in H.

Recommendation 3.2(b): We recommend that the project continue to broaden its theory-bases transport modeling, such as including pedestal physics and using other accepted models. In light of disagreements between various codes, additional benchmarking also needs to be done.

1. Participated in the ITPA Transport Workshop, continued interaction with Kinsey/Waltz on GLF23 , Bateman on Baldur/Ped Models, Hammett/Dorland on first principles models.
2. Working with the pedestal group (Osborne) to get a recommended pedestal model, or at least key sensitivities. ITB Model – GLF23 + Pedestal Model (Osborne ITPA-US)
3. Follow up at March ITPA Data Base and modeling meeting

Recommendation 3.3: We recommend that the project clearly explain the physics basis for selecting H(y,2)=1.1 to the larger plasma physics community.

1. Based on International Data Base, not on ITER Rules. The ITPA H mode Data Base provides stronger justification for FIRE assumption of H = 1.1 at n/n_{GW} = 0.6 than ITER-FEAT assumption of H = 1.0 at n/n_{GW} = 0.85.

2. Cordey paper at EPS-2001 and FIRE IAEA-2000 paper, also JT-60U operating space. Have discussed at ITPA.

4. Design Point

Finding 4.1 The PAC endorses the design point goals for the FIRE device as embodied in the 7.7 MA, 10 Tesla baseline design. The salient features of the design goals, with respect to the burning plasma mission, to reach Q of at least 10, corresponding to f_α of at least 2/3, where f_α is defined as the ratio of alpha heating power divided by total power input to the plasma. In order to test the approach of various regimes to steady state, the pulse length capability should be at least 2 current diffusion (skin) times at full parameters.

Recommendation 4.1 The project should characterize the confidence in achieving $Q \geq 5$ ($f_\alpha \geq 1/2$), which can be considered as the minimum performance needed to address the burning plasma missions. This assessment should be done in as quantitative a manner as possible, using both a range of scaling extrapolations and transport-based models.

Action 4.1: Project has adopted the 7.7 MA, 10T, R = 2.14m, A = 3.6, P_{fusion} = 150 MW design point.

1. While there is no accepted way of characterizing confidence in achieving the FIRE Mission, there are some exercises that will be useful. First and most importantly, performance and sensitivity will be measured in terms of f_α not Q.

a. likely best performance – present machines obtain physics results from a very small subset of total experiments, typically < 5 trophy discharges for a given major result which is a very small % (<< 1%) of the total number of discharges. The burning plasma experiments will be different with a much higher fraction of trophy discharges but a much smaller number of total shots (e.g., NIF, LMJ, etc C. Keane at APS-DPP UFA session). ITER-FEAT empirical projections are based on a very small number of good shots (~10) attained on JET out of total tokamak shot production of several million. So we are obviously talking about projections based on a small number of trophy shots. The question is, are these shots repeatable?

5. Physics R & D Plan

The project has made good progress in defining an acceptable FIRE design point based on the scientific objectives, and developing the physics scenarios that exploit the design capability. There are many scientific and technical questions raised by design and scenarios, and a physics R&D plan is needed to help in addressing these issues.

Finding 5.1: The PAC finds that no R&D plan has yet been established and that one is needed.

Recommendation 5.1 The PAC recommends that a physics R&D plan be developed and the items prioritized according to first those issues which impact the design point, and secondly those issues which increase the confidence in the design point.

Action 5.1: Physics R&D Plan is in progress, initial presentation at ITPA. This needs to be done in the December – January time frame to be of use to the Snowmass assessors.

6. Wedged Vs Bucked & Wedged Toroidal Field Design

Finding 6.0**:** The design team should be commended on providing innovative and well-analyzed "Wedged" and "Bucked & Wedged" PF-TF coil designs. Both designs optimize at different points in risk-benefit space and offer unique design choices for FIRE. We commend the project on the excellent and timely external engineering review of both designs.

Recommendation 6.1: The design team needs to summarize their excellent analysis in a document that clearly delineates the risk-benefits of each design. The summary should include documentation of all work done to date on each design. The summary should also articulate the reasons for why the design team has chosen the "Wedged" design as their primary design candidate.

Action 6.1: Final review held, decision ratified. summary document needs writeup. The FIRE Engineering Report is being updated and will include this section.

Recommendation 6.2: In view of the significant activities required to prepare an assessment of FIRE for the 2002 Snowmass meeting, the design team should focus on their preferred "Wedged" design

Action 6.2: Agreed, Wedged design point with an additional margin of 30% beyond the normal design margin as expressed in standard tokamak design criteria by Design Allowable.

LOWER PRIORITY ITEMS FOLLOW

7. Vision and Mission Statement(s)

The need for compelling vision and mission statements is acute for FIRE or any burning plasma effort to be pursued by the U.S. fusion community. The FIRE project has begun the process of developing a mission statement, and the effort is still ongoing. Hence, all of the recommendations (i.e., recommendations 2.1 through 2.3, PAC-2) regarding the mission statement and development of an overall mission description from the NSO-PAC 2 report are still in effect.

Finding 7.1: The informal survey of community members has resulted in some promising first suggestions for Vision and Mission statements, but the process is not complete. The initially proposed mission statement: “Attain, explore, understand and optimize fusion-dominated plasmas to provide knowledge for attractive magnetic fusion systems” is appreciated to be a good first step but is thought to be still too verbose. No consensus has emerged on any of the proposed Vision statements.
Finding 7.2: Additional efforts to produce a Vision and/or Mission statement will likely require input from sources outside the immediate fusion community.

Recommendation 7.1: Consider a shortened version of the proposed Mission statement as the working statement as the development process continues. One suggestion was: “Attain, explore, understand and optimize magnetically confined fusion-dominated plasmas”

Action 7.1: This has been adopted as the new mission.

Recommendation 7.2: Define a process or processes to reach out to a wider range of the scientific community and possibly the public to develop more compelling Vision and Mission statements. This may require a multi-faceted approach, such as a living poll n the FIRE web site to engage community members, soliciting advice from science reporters, creating small cross-cutting brainstorming panels form the science community, examining statements from equivalently-sized science programs, etc. While this is a problem for the whole fusion community, the FIRE project can catalyze the process while serving its own interests.

Action 7.2: Continued proactive visits to fusion sites and research groups, now 75 talks/discussions over the past three years. Discussions with Department Chairs, industrial contacts, with other fields during site visits. Interest has been developed but not yet achieving a critical mass. Initiated APS-DPP session on Burning Plasmas, AAAS session on Burning Plasmas being proposed.

8. Dimensionless parameters

Finding 8.1: The PAC commends the project for developing figures and tables showing the expected dimensionless parameters for the FIRE design, and for comparing them with those achieved on existing devices as well as those predicted for other next step proposal options.

Recommendation 8.1: The PAC recommends that the project consider the dimensionless parameter predictions in light of their physics implications. As an example, the parameter ($R\nabla\beta$) has been estimated, but the implications for Alfvén eigenmode stability are unclear.

Action 8.1: Criteria for $q^2 R\nabla\beta_\alpha$ are being developed, and will be displayed on PopCon plots. Mandrekas, Johner

9. Tangential Access

Finding 9.0: Tangential Access to the FIRE vacuum vessel could have significant benefits to machine operation, diagnostic access, and remote handling of vacuum vessel components. Recent experiments have shown the importance of plasma rotation, driven by tangentially injected neutral beams, on MHD mode control. Furthermore, diagnostic access was identified as a major issue at the Second Burning Plasma Science Workshop. Tangential access could benefit several important diagnostic techniques such as Charge Exchange Recombination Spectroscopy. .

Recommendation 9.0: Further cost-benefit analysis of incorporating tangential ports is required**.** The analysis should include the size of tangential ports possible and consistent with the present TF coil designs, the diagnostic field-of-view achievable, and the enhanced utility of using these ports for tangential beam injection and remote maintenance.

Action 9.0: Tangential ports will be evaluated for Snowmass

10. Auxiliary Power Requirements

The project presented a plan that reduced the total auxiliary heating power for FIRE from 30MW to 20MW. Lower H-mode threshold and reduced heating requirements from the recent H-mode power scaling make this possible.

Finding 10.1: The PAC is of the opinion that 20 MW appears marginal at providing access to desired operating space

Recommendation 10.1: We recommend that the capability to upgrade to 30 MW be maintained in all design aspects.

Action 10.1: 20 MW is believed to be adequate for the FIRE mission, the capability to add an additional 10 MW will be retained but is not considered as part of the baseline plan.

11. <u>Physics Modeling and Analysis</u>

Finding 11.1: The FIRE Project is to be commended for its progress in baseline physics analysis and modeling AT characteristics in FIRE. Significant progress was shown. However, questions remain concerning the following:

- A more consistent characterization of the position of the H-mode pedestal is necessary (i.e., at some point inside the last closed flux surface)
- It does not appear that the H-mode factor is consistent with edge power deposition
- The fast wave current drive efficiency implied by the calculations supplied by T.K. Mau appeared to be high

Finding 11.2: Progress was reported in illustrating the non-linear coupling in burning plasmas.

Recommendation 11.1: In the Q~5 AT cases:

- Establish target conditions for AT operation, specifically Q
- Include the H-mode pedestal more self-consistently
- Consider bootstrap current alignment and beta limits in accessing peaked density profiles
- Clarify the fast wave current drive efficiency

Action 11.1: Systems study survey, paper written for SOFE by C.Kessel etal. Also presentation at NSO-PAC4

Recommendation 11.2: More effort needs to be expended on examples of the non-linear coupling issues that can be examined in FIRE.

Action 11.2: A comprehensive simulation code needs to be developed with extensive visualization output capability. Hopefully, this can be done in stages rather than waiting for the completion of all modules at full physics capability.

12. <u>Diagnostics</u>

A successful burning plasma experiment will require profile and alpha diagnostics with good spatial and temporal resolution. The importance of these measurements to the successful execution of the FIRE scientific mission requires early and continuing consideration of diagnostic requirements and their impact on device design.

Finding 12.1: The interface for the diagnostics is expected to be a significant element of the design and total cost. The FIRE team has responded rapidly to the request for more integrated diagnostic planning in the FIRE design effort. A wide range of issues, including the impact of neutron environment on diagnostics, the need for improved and new alpha-particle measurements, radiation effects on diagnostic components, a conceptual port layout, and port access have been identified. The planning of the installation of the diagnostics to achieve the mission is beginning, but there is concern about the total impact of diagnostic needs on project costs.

Finding12.2: Some draft R&D proposals for diagnostics development issues have been identified. These include materials irradiation tests, new machine-components tests, and new or improved diagnostic techniques needs. Given the very long lead time of the needed development, it is important to identify critical R&D items related to FIRE plasma diagnostics (e.g., consideration of an intense diagnostic neutral beam, extended escaping alpha diagnostics, etc.). This will aid the evaluation of their impact on the FIRE design and encourage interest in these diagnostic challenges.
Finding12.3: Many of the machine diagnostics will require integration into the basic machine design since they will be inaccessible once fabrication is complete and operation commences. The impact such systems may have on machine design has not yet been considered in much detail. It is important to identify these issues during the design process so that critical diagnostic capabilities are not compromised.
Finding 12.4: The diagnostic considerations are understandably only partially developed to date. However, the consideration of very few divertor diagnostics implied to the committee that there is an overall lack of consideration of a divertor physics program.

Recommendation 12.1: The strategy for phased funding and implementation of the diagnostics needs continuing clarification. Most importantly, estimates of the initial costs of diagnostics during project design and construction and the total costs for diagnostics over the project lifetime are needed. It is understood that a large degree of uncertainty will exist for these efforts, especially since many details will not become evident until a conceptual design is available.

Recommendation 12.2: The project should identify critical research and development items for diagnostics on FIRE. It may want to explore enlisting the aid of the TPA group for this effort.

Recommendation 12.3: The initial machine design needs to incorporate diagnostic capabilities and requirements during the design process.

Recommendation 12.4: The project should develop at least a conceptual list of divertor science issues of importance to the FIRE program, and ensure that these issues are adequately considered in the design of diagnostics and their related port access.

Action 12.1- 12.4: A draft Diagnostics R&D plan has been prepared by Ken Young. FIRE diagnostics plans and issues were presented at the ITPA-Diagnostics meeting at St. Petersberg in November.

13. <u>Control of the Resistive Wall Mode</u>

Finding 13.1: Preliminary calculations using the VALEN code of a relatively simple active feedback control coil system added to the passive stabilizer in FIRE show it to be effective in stabilizing the RWM above the no-wall beta limit. For cases with all 16 port plugs removed, the RWM was predicted to be stabilized up to the ideal wall beta limit with use of 4 n=1 control coil pairs in 8 of the 16 mid-plane ports.

Recommendation 13.1: Further work is needed to assess the disruption loads on the control coils located in the mid-plane ports, the minimum required feedback amplifier gain for stabilization up the ideal wall beta limit, and the compatibility of control coils and RF antenna structures.

Recommendation 13.2: Work should continue to optimize the geometry of sensor and active mode control coils in FIRE and to extend the analysis of n=1 mode control capability FIRE to the analysis of higher n modes as well.

Action 13.1 – 13.2: Analysis work using VALEN is ongoing by the Columbia group, results presented in a paper by Bialek, Navratil et al at the APS-DPP meeting.

Recommendation 13.3: As noted in Finding 9.1 above, recent experimental work on the control of the RWM in DIII-D has shown the importance of toroidal plasma rotation. Inclusion of a toroidal momentum source in FIRE either from RF or NBI would be beneficial for the control of the RWM in conjunction with active feedback and a passive stabilizing structure. The possibilities for adding a source of toroidal momentum input on FIRE should be assessed.

Action13.3: This topic will be addressed in preparation for the Snowmass assessment.