Final

Next Step Options
Program Advisory Committee Report

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

Dr. Roger Bangerter, Chair
VLT Program Advisory Committee

From: Dr. Tony Taylor, Chair
NSO Program Advisory Committee

Date: January 31, 2001

Date and Place
The Next Step Options Program Advisory Committee (NSO-PAC) met Wednesday and Thursday, January 17 and January 18, 2001, at the Massachusetts Institute of Technology, in Boston, MA. This was the PAC's second meeting (PAC-2).

The next NSO PAC meeting (PAC-3) is tentatively scheduled to be held at the University of Wisconsin, Madison, WI, on Wednesday and Thursday, July 11 and 12, 2001.

PAC Members in Attendance:
Dr. David Gates, Dr. Wayne Houlberg, Prof. Tom Jarboe, Dr. Mitsuru Kikuchi, Dr. Earl Marmar, Dr. Raffi Nazikian, Dr. Tony Taylor, Dr. Paul Thomas, Dr. David Hill, Prof. Gerald Navratil, Dr. Craig Petty, Dr. Rene Raffray, Dr. James Van Dam

PAC Members not in Attendance:
Prof. Raymond Fonck, Dr. Kurt Schoenberg (2)

CHARGES FOR THIS MEETING

During this meeting, the NSO-PAC was asked to continue its consideration of the same four main charges that it had considered at its previous meeting: viz.,

1) What is the scientific value of a burning plasma physics experiment?
2) What is the scientific readiness to proceed with such an experiment?
3) Is the FIRE mission scientifically appropriate?
4) Is the initial FIRE design point optimal?

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

The chairman reminded the PAC that at its previous meeting (July 20 & 21, 2000), 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.

Gerald Navratil, chair of the organizing committee for the Workshop on Burning Plasma Science, presented a summary of the workshop to the PAC. The workshop was held in Austin, Texas, December 11-13, 2000, sponsored by the University Fusion Association. There were 90 participants. Workshop leaders wrote summary reports about alpha particle physics, self-heating and transport, MHD macro-stability, boundary plasma physics, and the relationship of fusion to other scientific fields. Copies of these reports in draft form were distributed to the PAC members.

The PAC adopted a proposal to establish an NSO-PAC subgroup consisting of Jerry Navratil, Raffi Nazikian, and Jim Van Dam, who will:

1. Take the UFA Burning Plasma Science Workshop report and
   — Merge the various break-out group responses to workshop questions #1 and #2 and draft a response to NSO-PAC Charge #1; and
   — Merge the various break-out group responses to workshop question #3 and draft a response to NSO-PAC Charge #2.
2. Circulate the draft to the NSO-PAC members for e-mail comment.
3. Add input, as appropriate, from the UFA Workshop on Burning Plasma Technology, which is planned to be held in April 2001.
4. Bring the finished draft to the next NSO-PAC meeting in July 2001 and finalize it there.

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

The PAC heard several presentations concerning the FIRE pre-conceptual design effort and its recent progress. The PAC offers the following comments.

1. Response to NSO PAC-1 Report

Representatives of the FIRE project presented an action plan for how to respond to issues that had been raised in the PAC-1 Report. This action plan addressed the PAC-1 findings and recommendations point by point. Additional information about the FIRE response was also presented at this PAC2 meeting.

Finding 1.1: We find that this action plan is a good framework for addressing the issues raised in the PAC-1 report.
Finding 1.2: Progress in implementing the action plan is limited to date. Some significant progress was made in assessing the cost reductions possible with the use of pure copper inner field conductors and in assessing the performance of FIRE under the ITER98(y,2) confinement

scaling law. Small perturbations around the design point were examined; however, optimization was not performed (e.g., the elongation was not varied when the aspect ratio was reduced).

Recommendation 1.1*:* Systematically vary the elongation while changing the aspect ratio. In so doing, take into account the effect of the bootstrap current.
Recommendation 1.2: Report further progress in addressing the PAC-1 issues at the next NSO-PAC meeting (see the annotated list in the Appendix to this report).

2. Mission Statement

The FIRE project presented a logical structure for developing its total mission statement: viz., vision, mission, objectives, physics parameters, device parameters, and cost. The project also proposed establishing an ad hoc working group of scientists from the community (specifically chosen from among the participants of the recent UFA Burning Plasma Science Workshop) to flesh out this logical structure for the FIRE mission.

Finding 2.1*:* 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 2.2*:* Also, as a major DOE scientific facility (if built), FIRE should have a broad scientific mission.
Finding 2.3*:* Issues that are listed in the PAC-1 report regarding the FIRE mission statement, but to which responses were not given at this meeting, are the following:

- Study of the 1/1 mode in FIRE would be a benchmark for analysis using full kinetic, energetic particle drive, and 2-fluid effects.
- What are the key parameters for alpha physics studies in FIRE— β_α/β, α-fraction, or other parameters? Does FIRE provide a significant advance in these parameters over present devices?
- Can FIRE study "burn control" issues?
- Can FIRE study transport barriers?

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

3. Plasma dimensionless parameters

Finding 3.1: The FIRE project team has correctly identified the appropriate dimensionless quantities (alpha heating fraction and ratio of flattop time to current diffusion time) to guide the

design study. It is appropriate to neglect other time scales such as that for plasma-wall interactions and the L/R time.
Recommendation 3.1: The team may want to consider adding another dimensionless parameter (e.g., maximum R β_α , magnetic shear) that might better characterize the machine's ability to address alpha physics.

Finding 3.2: While the project has clearly started to define the reasons for selection of dimensionless plasma parameters, it still lacks a clear presentation on the range of parameters that can be obtained and that will allow the machine to achieve its scientific objectives.
Recommendation 3.2: We recommend that the project work to communicate this information better as these studies come to fruition. A table showing the range of key dimensionless parameters would be helpful.

Finding 3.3: The project has not clearly shown how the FIRE operating point compares, in dimensionless parameters, to those for existing tokamaks and planned future machines.
Recommendation 3.3: The FIRE team should develop extensive tables (at constant beta and collisionality) to show clearly where the device is positioned between existing experiments and other future devices, in order to show how big a step it represents.

4. Confinement scaling

Finding 4.1: 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.
Recommendation 4.1(a): 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.
Recommendation 4.1(b): The project should look at how robust the projected operating point is to variations in choice of scaling relations.

Finding 4.2: We endorse the use of 10% higher confinement and a slightly peaked density profile ($n(0)/<n>=1.2$) in the baseline projections for FIRE, noting that peaked profiles have been shown clearly and the better confinement is well within the range of existing data.
Recommendation 4.2: We recommend that the project clearly document the basis for these choices for presentation to the larger plasma physics community.

Finding 4.3: We endorse the initial theory-based transport modeling of FIRE plasmas; however, we note that some key H-mode physics may be missing (e.g., edge pedestal physics).
Recommendation 4.3: We recommend that the project should broaden its theory-based transport modeling, such as including pedestal physics and using other accepted models.

5. Design Point Studies

Finding 5.1: We commend the project for starting work on comprehensive design point studies using a systems code and a 0-d model (which should be benchmarked against each other).
Recommendation 5.1(a): The project needs to present more clearly what key parameters drive the design point and what sets the limiting value for each. Examples of such key parameters are:

- $f_\alpha = P_\alpha/P_{heat}$
- discharge duration ($2\ \tau_{CR}$)
- wall loading ($\leq 3 MW/m^2$)

Recommendation 5.1(b): The project should extend the design point studies down to an aspect ratio of 3 with fixed mission.
Recommendation 5.1(c): The project should look at the incremental cost of meeting the various mission objectives. What is the relative cost of doing Q=5 versus Q=10, or $2\tau_{CR}$ versus τ_{CR} , or implementing the AT control tools? What are the trade-offs?

6. Design Point

The project has made good progress in defining the 7.7 MA FIRE design point based on the scientific objectives. A clearer delineation is needed showing how each scientific objective drives the specific choice of machine parameters. In addition, device flexibility and the range of possible operating regimes should be assessed. Issues to be addressed include:

a) What is the operational margin with respect to Q for operation at de-rated parameters?
b) Assess the reliability for operation near the maximum parameters of current and magnetic field .
c) What breadth of parameters can be expected, given fixed values of Q (e.g., Q=5, Q=10, Q>10)?
d) Density and density profile are two very strong controlling parameters for determining the fusion power production. What tools will be available for density and density profile control?

7. FIRE* versus FIRE

The PAC was presented with three possible modifications to the 6.4 MA FIRE design that would allow operation at 7.7 MA (FIRE*). The three different approaches were: increase the toroidal field; increase the shaping, primarily triangularity; increase the size and inverse aspect ratio. This study was implemented in response to the PAC recommendation that performance be assessed using the ITER(y2) 0-d confinement scaling law, which leads to a 15% degradation relative to that predicted from earlier scaling relations.

***Finding 7.1**:* The committee endorses the increase of plasma current capability.

Recommendation 7.1: The project needs to define how selection among these three options will be made, taking into consideration cost, flexibility, and technical constraints.

Recommendation 7.2: We commend the project for planning peer review of the engineering aspects of the design, and we encourage the prompt scheduling of these reviews.

8. Physics Analysis and Device Flexibility

Finding 8.1: The FIRE design team is commended for making significant progress in defining the AT physics operational regimes that are accessible to the current FIRE design, as well as defining the additional tools that may be required in the area of density, current, and pressure profile control.

Finding 8.2: Significant progress has been made in determining the range of q-profiles for the basic FIRE design, based on dynamic simulation analysis of the plasma startup. The analysis indicates that MHD-stable regimes of interest for enhanced confinement and Alfvén eigenmode studies may be accessible with careful programming, and maintained for the duration of the discharge.
Recommendation 8.2(a): Further time-dependent plasma evolution studies are required in order fully explore the range of current profiles accessible to the base design and the further scientific benefit of profile control systems such as LHCD. A realistic lower hybrid current drive model needs to be used to assess the LHCD power requirements.
Recommendation 8.2(b): The assessment of additional profile control tools should be based on more detailed physics analysis of the phenomena (e.g., Alfvén eigenmodes) that can be studied.
Recommendation 8.2(c): It is recommended to assess the MHD stability with stronger edge pedestals than used in the simulations.

Finding 8.3: The AT conditions for FIRE were defined by the minimum plasma current at which alpha losses are acceptable with reverse shear operation (8.5 T, 6.4 MA). Extended operation for at least 3 resistive skin times is possible at these parameters with inductive operation. AT regimes with reverse shear and Q=5 were shown to be close to the free-boundary stability limit. A central issue raised is the question of what additional capabilities (e.g., resistive wall mode stabilization) are required to maintain flexibility for enhanced AT physics capability.
Recommendation 8.3(a): A strong recommendation of our committee was to assess the maximum feasible I/aB accessible for FIRE (i.e., maximize δ, κ, ε). This would allow the design to maximize the confinement and plasma pressure and to take advantage of recent developments in the optimization of the AT concept.
Recommendation 8.2(b): The committee recommends the study of AT scenarios at higher q-95 and I_{BS} in order to reduce the current drive requirements.
Recommendation 8.2(c): The trade-off between enhanced physics capability and additional cost needs to be assessed in the light of the PAC-1 recommendation that the primary burning plasma mission be preserved within the foreseen capital cost.

Finding 8.4: A key aspect of the scientific mission of FIRE is to define the operating range (range of physics and engineering parameters) required for achieving the scientific mission.
Recommendation 8.4(a): Define the range of parameters (e.g. alpha pressure, q-profile) needed to access relevant physics regimes, and express these in terms of POPCON diagrams for AT and H-mode regimes.

9. Diagnostics

Finding 9.1: A successful burning plasma experiment will require profile and alpha diagnostics with good spatial and temporal resolution. The interface for the heating systems and diagnostics is a significant element of the design and total cost. The FIRE team stressed the major technical challenge of designing and installing diagnostics that will operate under irradiation corresponding to a neutron wall load of 3 MW/m^2. The project is aware of the serious consequences for diagnostics. Two areas that were identified as needing further research are radiation effects on ceramics and on optical fibers. A major issue is the planning of the installation of the diagnostics to achieve the mission.
Recommendation 9.1(a): The diagnostic planning and resource requirements need to be defined within the context of the scientific mission. The strategy for phased funding and implementation of the diagnostics needs to be clarified.
Recommendation 9.1(b): A machine layout and port allocation needs to be determined early in the design process, and port plugs designed to be consistent with the later requirements.

Finding 9.2: A diagnostic neutral beam (5 GW, 1ms pulsed, 300 keV) may be required for MSE and other profile measurements. This system would entail significant additional cost.
Recommendation 9.2: Assess the cost of a diagnostic neutral beam incorporated into the baseline design, or assess how profiles can be measured without it.

10. Bucked/Wedged Toroidal Field Design

The FIRE project presented an advanced analysis of the bucked/wedged alternative TF design. Such a design has the potential advantages of reduced power supply requirements, longer pulse length, lower conductor costs, and possibly simplified conductor design.

Recommendation 10.1: We recommend that the cost and risk trade-offs be more clearly detailed at the next PAC meeting.

APPENDIX

Response to Additional Specific Comments (in the PAC-1 Report) Concerning the FIRE Design Point:

Partial response provided:

- *Develop a table of key dimensionless parameters and their values expected in FIRE and compare them for existing experiments, proposed experiments, and the reactor goal.*
  Preparation of such a table is underway. A preliminary version was presented.

- *The capability to study AT modes needs to be clarified, in terms of magnetic topology flexibility, current profile control, transport control, density control, rotation control, and so forth.*
  AT capability in terms of current profile control was examined.

Essentially completed:

- *Identify potential upgrades. The base design should at least support exploration of AT plasmas.*

Several AT-relevant upgrades involving lower hybrid and fast wave current drive were identified and their costs estimated. Provision for active control of resistive wall modes was described.

- *Firm up the cost estimates of tritium systems. The current estimates (~$30 million) seems low relative to the cost of such systems on TFTR.*
  The FIRE project would use the TFTR tritium system.

No response yet:

- *Define the range of operation needed to explore the physics of neoclassical tearing modes, alpha particle-driven instabilities (e.g., TAE), and other MHD issues.*
- *Run transport simulations for the design point.*
- *The capability to study AT modes needs to be clarified, in terms of magnetic topology flexibility, current profile control, transport control, density control, rotation control, and so forth.*
- *Evaluate helium ash accumulation issues, especially for advanced modes*
- *Examine the existing database for double-null divertor tokamaks concerning up-down/in-out power asymmetries during disruptions.*
- *Develop a better characterization of disruptions, vertical disruption events (VDE), electromagnetic loads, and other effects, as well as their consequences on the design point.*
- *Assess runaway electron production during disruption in FIRE and develop mitigation plans if necessary.*
- *Clarify the pumping requirements for FIRE. There is ambiguity in what was presented.*
- *Eliminate carbon first-wall components in FIRE in order to minimize tritium retention. The Committee supports this approach.*
- *Develop a plan for re-coating beryllium walls periodically in the event that migration of tungsten to the first-wall surfaces introduces unacceptable levels into the plasma.*

Final

- *Analyze the effect of ELMs on the divertor plates.*
- *Plan for FIRE experimental operations, taking into account the relatively low rate of full-power shots. This may require a shift in experimental strategy toward the ICF paradigm, which involves more pre-operational simulation prior to each full-power, long-pulse shot and more complete single-shot diagnostic coverage.*
- *Clarify the trade-off between the lifetime limits on pulse number and pulse length.*
- *Include error field correction coils in the design, and assess if these could be used for n=1 feedback control.*
- *Determine the power supply requirements for n=0 control with the use of the specified passive and active control coils.*
- *Consider providing tangential port access.*