U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.
2104

2. REVISION. NO.
0

3. DATE PREPARED
2/29/04

4. WORK PROPOSAL TITLE
Next Step Options

5. BUDGET AND REPORTING CODE
AT6010501

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
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8. HEADQUARTERS ORGANIZATION:
Office of Science

9. OPERATIONS OFFICE:
Chicago Operations Office

10. CONTRACTOR NAME:
Princeton University
Princeton Plasma Physics Laboratory

11. DOE HQ ORGANIZATION CODE:
SC

12. DOE OPS OFFICE ORGANIZATION CODE:
CH

13. CONTRACTOR CODE:
15

14. WORK PROPOSAL DESCRIPTION:

The purpose of the national Next Step Options (NSO) design studies is to:

- Advance the physics and engineering design of FIRE for the study of burning plasmas to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas.
- Support the evaluation of candidate fusion program next step options to determine their feasibility, scientific merit and estimated costs as candidates for a new DOE construction project, or for U. S. participation in an international collaboration/cost-shared project.
- Integrate these options into a coordinated multi-element program as input to program planning activities.

The U.S. is presently a participant in the negotiations to decide on a site for the construction of ITER. It is anticipated that a decision on proceeding with ITER will be made by the end of FY04. If the ITER process has not arrived at a decision, then FIRE would be advanced as an alternative to ITER. The NSO Plan for FY05/06 follows the Dual Path Strategy recommended by the FESAC and the draft Energy Policy Act introduced in the Senate in February 2004. The NSO study, a national activity organized by the VLT, includes PPPL along with the other fusion laboratories and universities and a small but important industrial element. This Field Work Proposal discussion covers this national activity, including budget estimates for PPPL work.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

TECHNICAL PROGRESS IN FY 2004

As a result of reviews and recommendations by the NSO PAC and the 2002 Snowmass Summer Study on Fusion, the design point for FIRE has been established at R = 2.14 m, a = 0.595 m, $B \leq 10$ T, $I_p \leq 7.7$ MA, $P_{alpha}/P_{heat} > 0.66$ ($Q \geq 10$), with $P_{fusion} \sim 150$ MW for burn times > 20 s. This hardware capability provides adequate capability to explore burning plasma physics in the conventional Elmy H-mode, hybrid mode and advanced tokamak mode with dimensionless parameters approaching those of ARIES advanced tokamak (AT) regimes. A flexible and robust engineering design has been achieved for FIRE that provides a substantial margin for the magnet systems and has large access ports for remote maintenance and diagnostics. The basic FIRE design incorporates advanced tokamak features including strong shaping, very low toroidal field ripple, inside launch pellet injection, internal control coils and innovative close coupled RWM stabilization coils. The tokamak fusion core is estimated to cost $350M including a 25% contingency. The total construction project is estimated to cost $1B assuming $200M of site credits.

Since the submission of the last FWP in April 2003, the FIRE Team has responded to recommendations from Snowmass and has been an active participant in the International Tokamak Physics Activity (ITPA). For conventional H-mode operation, FIRE has essentially the same physics capability as ITER, namely $Q \approx 10$ with a burn time of two current redistribution times [86% J(r) equilibration]. At Snowmass, the technical basis for FIRE was confirmed after two weeks of detailed review with the summary conclusions:

- There is confidence that ITER and FIRE will achieve burning plasma performance in H–mode based on an extensive experimental database.
- ITER and FIRE scenarios are based on standard ELMing H–mode and are reasonable extrapolations from the existing database."

From its inception, FIRE was envisioned as a stepping-stone from existing AT experiments (DIII-D, C-Mod, AUG, JET and JT-60U) to ARIES-RS, the U.S. vision for an attractive fusion power plant. During the past year, FIRE has made significant advances in developing a high-beta high-bootstrap advanced tokamak mode that would approach the advanced tokamak mode required for an attractive steady-state reactor like ARIES-RS ($\beta_N \sim 4.8$, $f_{bs} \sim 90\%$). The FIRE AT mode involves a reversed shear profile that is sustained in a 100% non-inductive stationary state by ~80% bootstrap current, with 15 % LHCD and 5% ICFW for detailed profile control. A collaboration with Columbia University employed the VALEN code to show that the FIRE AT mode could be stable to n=1 resistive wall modes for $\beta_N \leq 4.2$. An advanced tokamak system code based on 0-D power balance and engineering constraints on power handling was developed to determine the AT operating range. The FIRE AT operating range extends up to $\beta_N \sim 4$, $f_{bs} \sim 80\%$ with Q = 5 to 10 for plasmas sustained for 4 to 5 current redistribution times. This is significantly beyond the present AT operating range ($\beta_N < 3$, $f_{bs} \sim 50\%$) of ITER. Time dependent simulations of FIRE AT discharges were carried out using the Tokamak Simulation Code (TSC). "Steady-state" discharges with plasma current profile constant for over 3 plasma current redistribution times were produced using a programmed plasma current rise that produced the desired current profile at the beginning of the flat-top. This work has been presented at the 19^{th} IAEA Fusion energy Conference at Lyon and at the

Table I. Advanced Tokamak Parameters

	ITER-AT	PPCS-C	FIRE-AT	ARIES-RS
R (m), a (m)	6.35,1.85	7.5,2.5	2.14, 0.595	5.52, 1.38
κ_x , κ_a , κ_{95}	, 1.85 ,	2.1, 1.9,	2.0, 1.85,1.82	1.9, - ,1.70
δ_x , δ_{95}	, 0.40,	0.7, 0.47,	0.7, 0.55	0.77, 0.5
Div. Config., material	SN, C(W)	SN, W	DN, W	DN, W
$(P_{loss})/R$ (MW/m)	15	~70	16	80
$B_t(R_o)$ (T), I_p (MA)	5.1, 9	6, 20	6.5, 4.5	8, 11.3
$q(0), q_{min}, q_{95}$	3.5, 2.2, 5.3		4, 2.7, 4.0	2.8, 2.49, 3.5
β_t(%), β_N , β_p	2.8, 3.1, 1.5	5, 4 ,	4, 4.1, 2.15	5, 4.8, 2.29
f_{bs} (%)	48	69	77	88
Non Inductive CD. %	100	100	100	100
$n(0)/\langle n\rangle_{vol}$, $T(0)/\langle T\rangle_{vol}$	1.5,	1.5,2.5	1.5, 3.0	1.5, 1.7
n/n_{GW}, $\langle n\rangle_{vol}$ (10^{20} m^{-3})	0.8	1.5	0.85, 2.4	1.7, 2.1
$T_i(0)$, $T_e(0)$	31	40	14, 16	27, 28
Z_{eff}	2.1	2.2	2.3	1.7
H98(y,2)	1.6	1.3	1.7	1.4
τ_E, (s)	3.1		0.7	1.5
Burn Duration/τ_{cr} , s	10, 3000	Steady-state	3.2, 40	Steady-state
$Q = P_{fusion}/(P_{aux} + P_{OH})$	6	30	4.8	25
Fusion Power (MW)	360	3400	140	2160
P_{fus}/Vol (MWm^{-3})	0.45	1.9	5.5	6.2
Γ neutron (MWm^{-2})	0.5	2.2	1.7	4

30th EPS on Controlled Fusion at St Petersburg, Russia. The FIRE-AT parameters approach those of the ARIES-RS design as shown in Table I.

Work has continued on a number of issues identified at the Snowmass meeting including: power handling during ELMs and disruptions, increased capability for neoclassical tearing mode stabilization, increased AT capability and pulse length, and increased operational flexibility. FIRE has been an active participant in Alcator C-Mod experiments on comparison of plasma behavior in single null and double null configurations, and has followed up on the studies of elm reduction in double null divertor configuration on ASDEX and DIII-D.

The FIRE budget was reduced significantly in FY 2004, and the engineering activities were limited to updating the Engineering report for the 2.14m design point and extending analyses of disruption loads. Work in the PFC area was carried out in collaboration with the base program and the ITPA activities.

The FIRE Team also participated actively in national and international meetings including SOFE (8 papers), EPS 2003, APS-DPP 2003, and the International Tokamak Physics Activity (ITPA) meetings. FIRE has taken the lead in organizing a special session at the Spring meeting of the APS in Philadelphia (2003) and a special session of the AAAS on Burning Plasma Physics (2004). During the past year, the FIRE Team has presented > 20 talks and >8 conference papers. The FIRE web site has served as a repository for fusion program information as well as FIRE documentation.

In late FY 2002, FESAC recommended that in parallel to the ITER activities, FIRE "should proceed to a physics validation review, as planned, and be prepared to initiate a conceptual design by the time of the U.S. decision on participation in ITER construction." A FIRE Physics Validation Review (PVR) is planned for mid FY 2004 to review the capability and flexibility of FIRE to answer the critical burning plasma issues, and to determine what areas are deficient and what remedies are recommended. The PVR will also identify what areas need supporting R&D from the base program (experimental, theory and modeling).

FY 2005 PLANS

The negotiations on plans to construct ITER were scheduled to be completed by the end of December 2003. However, the decision process has been deadlocked with the hope that a decision will be made by the end March 2004.

Plan A: If a decision is made to construct ITER, and the U.S. joins the ITER project the NSO activities will complete its FIRE mission, and will transfer resources to address other areas within the NSO charter. These areas include: coordination and development of burning plasma physics activities in support of exploiting the full capability of ITER and uniform assessment of burning plasma physics issues for plasma based neutron sources based on tokamak physics and engineering design experience.

The thrust of the FY 2005 NSO activities will be to make progress on the resolution of generic burning plasma issues needed for ITER (and CTF) with an emphasis on those required for an attractive tokamak fusion power plant presently envisioned by ARIES-RS. This would include:

- development and optimization of metallic PFCs,
- development of RWM technology (insulation, feedback control,..)
- disruption mitigation techniques under high power density conditions
- plasma engineering (ICRF, LHCD, Pellets, ..)
- development of diagnostics for FIRE and ITER (esp. AT modes)

A specific goal will be to demonstrate the feasibility of at least one ARIES-like AT scenario for ITER including RWM stability analysis and a feasibility study of close coupled RWM coils with compatible plasma facing components for each device. Another area of emphasis will be the development of plasma facing components, first wall and divertor configurations capable of handling high p0wer densities with low tritium retention

In addition, NSO will coordinate with the Sci-DAC on the simulation of burning plasma phenomena. The nonlinear coupling among: the plasma pressure profile defined by alpha heating, the self generated plasma current and the plasma transport is the critical issue for an attractive fusion power plant. The Fusion Plasma Simulator would also be of great benefit to designing, and interpreting the detailed results for a burning plasma experiment.

The resources needed to carryout a minimal program in this area is: $500k at PPPL and $200k at Sandia and MIT. The present DOE plan is to deal with ITER support proposals outside the institutional Field Work Proposal process.

Plan B: If a decision to build ITER, under conditions acceptable to the US, is not concluded within FY 2004, then FIRE should "be advanced as a U.S.-based burning plasma experiment with strong encouragement of international participation" as recommended by FESAC, and in accordance with the Energy Policy Act of 2003 now before the U.S. Senate. The major activities would include:

- formation of a national FIRE organization to manage the FIRE activities
- initiation of discussions with potential international collaborators
- form FIRE Project Management team
- initiate Conceptual Design Activities
- initiate R&D program in support of FIRE Conceptual Design Activities
- initiate studies of potential construction sites for FIRE

The goal of these activities would be to complete the FIRE Conceptual Design Activities by the end of FY 2006. Based on prior experience with conceptual designs of similar size devices such as CIT and TPX, the Conceptual Design for FIRE as a U.S. based burning plasma experiment is estimated to cost ≈$15M and take ≈15 months after initiation. These activities would rely heavily on the past experience and the core competencies of the U.S. in carrying out burning plasma designs. These capabilities reside at the major fusion laboratories, Universities and U.S. industries. For the FIRE Conceptual design activities the most expeditious way to proceed is to expand activities already underway and add participants as needed with experience in key areas. A duration of 18-24 months is reasonable, if adequate planning is carried out during the latter part of FY 2004.

The incremental funds requested for supporting Plan B are shown in Table 2.

Budget ($M)	FY 2003	FY 2004	FY 2005	FY 2006
NSO/FIRE Guidance	0.81	0.0	0.0	0.0
Snowmass 2002	0			
FIRE Conceptual Design		.39	2/6	4/12
Actual	0.81/3.16	0.39/0.6		

Table 2. **Plan B** – PPPL/National NSO(FIRE) Budget Request

<u>FY 2006 PLANS</u>

Plan A Burning Plasma Initiative

The planned work scope for FY 2006 would address key technical issues that are generic to any next step option for studying burning plasmas or producing fusion neutrons at high power densities. (see FY 2005) This will be part of the ITER R&D and burning plasma support that is being proposed through a different venue.

Plan B NSO(FIRE) Conceptual Design
The major FY 2006 activities would include:

- formation of an international collaboration on FIRE activities, possibly as part of an international multi-machine program.
- completion of the Conceptual Design and update of the cost estimate including possible cost sharing/reductions due to international participation
- review of possible construction sites for FIRE

<u>RELATIONSHIP TO FESAC GOALS</u>

A burning plasma experiment would make unique contributions to FESAC Goals 2, 3 and 4. The major contribution is Goal 3, to advance understanding and innovation in high-performance plasmas….). FIRE as an example of an advanced tokamak at the frontier of fusion science would also contribute to resolving scientific issues with a reduced cost development path and would drive enabling technologies for innovative solutions leading to an improved vision for fusion. A burning plasma acts as the ultimate test of the science basis by **integrating** and testing the understanding several goals simultaneously.

The most relevant Five Year FESAC Objectives for NSO/FIRE are:

3.3.3: BURNING PLASMA: 5-Year Objective: Develop and assess burning plasma scenarios and potential next step burning plasma options utilizing domestic resources and working in concert with international collaborators. Progress will be measured by the technical readiness of next step options for a burning plasma physics experiment.

3.4.1 ENABLING PLASMA TECHNOLOGIES 5-Year Objective : Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma measurements, heating, current drive, flow control, and fueling; develop plasma facing components; study improvements in magnet technology which could lead to significant reductions in the cost of fusion systems. The R&D required for a next step burning plasma experiment will drive progress in enabling plasma technologies.

3.4.2.1 ADVANCED DESIGN: Carryout engineering design work and system optimization studies for next step burning plasma devices: Identify and understand key issues that need to be addressed, resolve technical issues and be ready to move forward with participation in a next step burning plasma experiment. The ARIES work serves as a beacon to guide the general direction for FIRE.

MILESTONES

The milestones for the national NSO/FIRE activities are summarized below. The PPPL specific milestones would be derived from these milestones in terms of physics and engineering analysis required.

Baseline Budget Milestones

Physics Validation Review	Mar 04
Decision on ITER Construction	Jul 04

Plan B: If ITER does not proceed under terms suitable to U.S.

CD-0 Approve Mission Need	Oct 04
Community Workshop on Prep for FIRE Conceptual design	Nov 04
Finalize Plan for FIRE Conceptual Design	Nov 04
Initiate FIRE Conceptual Design	Dec 04
Completion of FIRE Conceptual design	Jun 06
CD-1 Approve preliminary range	Aug 06
Begin Preliminary Design	Oct 06