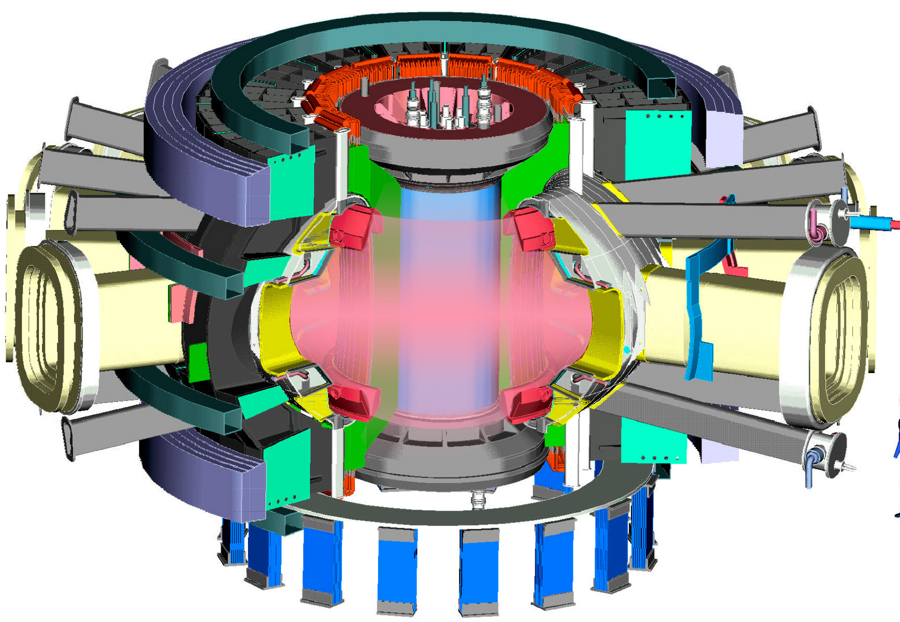
Fusion Ignition Research Experiment Highlights



Fusion Ignition Research Experiment

FY 2004

Need for a Burning Plasma Experiment

In 2002, the National Research Council (NRC) under the auspices of the National Academies formed a Burning Plasma Assessment Committee (BPAC) that found: "A burning plasma experiment is critically needed to advance fusion science," and recommended that: "The United States should participate in a burning plasma experiment. Participation in a burning plasma experiment is a critical missing element in the U.S. fusion program. The scientific and technological case for adding a burning plasma experiment to the U.S. fusion science program is clear. There is now high confidence in the readiness to proceed to the burning plasma step because of the progress made in fusion science and fusion technology. Progress toward the fusion energy goal requires this step, and the tokamak is the only fusion configuration ready for implementing such an experiment."

In accordance with the NRC-BPAC and Fusion Energy Sciences Advisory Committee (FESAC) recommendations, the US has joined the international negotiations to determine the site, cost sharing and management structure of the International Thermonuclear Experimental Reactor (ITER). In addition, pre-conceptual design work on the Fusion Ignition Research Experiment (FIRE), a backup burning plasma experiment, is being carried out in the U.S. as recommended by the NRC-BPAC and FESAC.

The goal of the FIRE pre-conceptual design study is to define a low-cost (~$1B) burning plasma experiment to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas. The key technical objectives for FIRE are to address the critical burning plasma issues of an attractive magnetic fusion power plant as envisioned by the Advanced Reactor Innovation Evaluation Studies (ARIES). The FIRE Design study has been undertaken as a national collaboration with over 50 participants from more than 15 U. S. institutions, and is managed through the Virtual Laboratory for Technology. The technical work on FIRE has been guided by a Next Step Option Program Advisory Committee (NSO-PAC), with members from 12 U.S. fusion institutions and as well as Europe and Japan.

Community Assessment of FIRE as a Next Step Burning Plasma Experiment

At the 2002 Fusion Summer Study at Snowmass of nearly 300 fusion scientists, there was a strong consensus behind the central finding that: "The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science. The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research." A thorough technical assessment by 10 working groups also provided a very positive assessment of the FIRE mission and capability. Most importantly, the Technical Assessment concluded that there are no outstanding engineering-feasibility issues to prevent the successful design and fabrication of FIRE, and that there is confidence that FIRE will achieve burning plasma performance in the conventional H–mode. Based on 0D and 1.5D modeling, all three devices (ITER, FIRE and IGNITOR) have baseline scenarios which appear capable of reaching $Q = 5 - 15$ with the advocates' assumptions. ITER and FIRE scenarios are based on standard ELMing H–mode and are reasonable extrapolations from the existing database.

Snowmass also affirmed the advanced tokamak features of FIRE by noting that: "Recent physics advances in tokamak research, aimed at steady-state and high performance, demonstrate the potential to significantly increase the economic attractiveness of the tokamak. Therefore, Advanced Tokamak (AT) research capability is highly desirable in any burning plasma experiment option." "ITER and FIRE have moderate- and strong-shaping respectively and the control tool set needed to address the issues of high beta and steady-state related to Advanced Tokamak regimes. FIRE has the capability to sustain these regimes for one to three current redistribution times (τ_{CR}), while ITER has the capability to sustain these regimes for up to 3000 s allowing near steady-state operation." Additional work on FIRE after Snowmass developed AT regimes that could be extended up to 5 current redistribution times (see later section).

A number of technical issues have been identified and are documented in the body of the Snowmass report. For example: for both ITER and FIRE, the predicted ELM-power loads are at the upper boundary of acceptable energy deposition, therefore ELM-control and amelioration will be needed. On FIRE, control of the neoclassical tearing mode (NTM) by lower hybrid current drive is not sufficiently validated. Also, FIRE has a concern about radiation damage of magnet insulators (for extensions of the experimental program beyond the original scope). While on ITER, tritium retention is a concern with the proposed carbon-based divertor materials. These issues are being addressed by continuing R&D activities.

A multi-machine development path based on a FIRE burning plasma experiment, a non-burning very long pulse advanced tokamak (e.g., KSTAR, and JT-60 SC), a component test facility with a fusion plasma simulator was developed and presented at Snowmass. The Snowmass assessment found that the "FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions. It is a lower risk option as it requires "smaller" extrapolation in physics and technology basis. Assuming a successful outcome, a FIRE-based development path provides further optimization before integration steps, allowing a more advanced and/or less costly integration step to follow." This plan was expanded to include cost profiles and was presented to the FESAC Development Path Panel.

A Robust U.S. Fusion Strategy for Burning Plasma Research

In September 2002, FESAC recommended to DOE a robust strategy endorsed overwhelmingly by a FESAC Panel consisting of 44 fusion community leaders. FESAC found that:

> ITER and FIRE are each attractive options for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths.
>
> Because additional steps are needed for the approval of construction of ITER or FIRE, a strategy that allows for the possibility of either burning plasma option is appropriate.

Since FIRE is at an advanced pre-conceptual design stage, and offers a broad scientific program, we 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.

If ITER negotiations succeed and the project moves forward under terms acceptable to the U.S., then the U.S. should participate. The FIRE activity should then be terminated. If ITER does not move forward, then FIRE should be advanced as a U.S.-based burning plasma experiment with strong encouragement of international participation.

U.S. Plan for the Development of Fusion Energy

In March 2003, FESAC recommended a plan for the development of fusion energy with the end goal being the operation of a demonstration power plant starting in 35 years. A burning plasma experiment is a critical element of the FESAC Plan. "Either ITER or FIRE could serve as the primary burning plasma facility, although they lead to different fusion energy development paths. If ITER goes forward it will fulfill all of the requirements for an MFE burning plasma experiment. Should ITER not move forward, the plan calls for construction of the domestic burning plasma experiment, FIRE."

FESAC also noted that: "A FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions. This option aims at smaller extrapolations in physics and technology. Assuming a successful outcome, a FIRE-based development path provides for additional optimization before further integration steps are needed, allowing a more advanced and/or less costly integration step that will follow."

"From the perspective of the total cost to the U.S. for the development of commercial fusion energy, the difference between the FIRE and ITER paths is relatively minor."

The NRC-BPAC recommended that the U.S. develop other options for a burning plasma experiment, in the case the negotiating parties do not approve ITER construction. The FIRE concept represents one possible contingency that could be revisited in this context. Congress also expressed interest in fusion with the Energy Policy Act of 2003, which is currently before the Senate. This bill would authorize doubling of the fusion science program budget over five years and U.S. participation in ITER as a burning plasma experiment. If the Secretary of Energy determines that construction and operation of ITER is unlikely or infeasible, then a plan for implementing the domestic burning plasma experiment known as FIRE should be sent to Congress.

FIRE is being Designed to Address Burning Plasma Physics Relevant to an Advanced Fusion Reactor

The Advanced Reactor Innovation Evaluation Studies (ARIES) studies have shown that an economically attractive tokamak power plant will require >80% plasma self-heating with more than 90% of the confining magnetic field to be self-generated. The overall theme of FIRE is to test the advanced tokamak features identified by the ARIES studies as being essential to the development of an attractive tokamak power plant. The basic parameters of FIRE were chosen to make FIRE a 40% scale model test of the ARIES-RS physics design (Table I). The projected FIRE plasma parameters are close to the parameters of ARIES and would provide a valuable facility for exploring the physics of reactor-like burning plasmas.

Table I. Comparison of FIRE Advanced Tokamak Parameters with ARIES-RS

Parameters	**FIRE**	**ARIES-RS**
κ_x plasma elongation	2.0	2.0
δ_x plasma triangularity	0.7	0.7
Divertor Configuration	DN	DN
β_N, normalized beta, AT mode	~4	4.8
Bootstrap fraction, AT mode	80	88
Non-inductive Current Drive, %	100	100
Plasma Current Profile Equilibration (%)	86 - 99	100
B (T)	6.5 - 10	8
R (m)	2.14	5.5
Plasma Volume, m^2	27	350
P_{fusion}/Vol (MW/m^3)	5.6	6.2
Neutron Wall Loading (MW/m^2)	2.7	4
Divertor Power Load P_{loss}/ R_x(MW/m)	20	100
Divertor Target material	W	W

Since Snowmass, there has been significant progress made in improving the physics basis for FIRE. Results from ongoing tokamak experiments continue to indicate that strong plasma shaping, as present in FIRE, promotes increased H-mode confinement, enhances β limits and reduces the deleterious edge localized mode (ELM) to a more benign form.

The area of greatest progress on FIRE has been the development of a "steady-state" high-β AT configuration. The "steady-state" high-β AT configurations in FIRE rely on ICRF Fast Wave (FW) on-axis current drive and lower hybrid (LH) off-axis current drive. The ICRF system can provide 200 kA of current by injecting 20 MW of power with the existing two-strap antenna design. Typical AT plasmas require less than 200 kA of on-axis current drive. Upgrades to four strap antennas would improve the CD efficiency. Off-axis current drive in FIRE is critical for establishing and controlling the safety factor profile, and is accomplished using up to 30 MW of LHCD at 5 GHz. The experience developed on Alcator C-Mod advanced tokamak experiment with lower hybrid current drive will strengthen the basis for FIRE projections.

Bootstrap and external current drive consistent equilibrium and stability analysis show that the high-n ballooning limit for typical plasmas is $\beta_N > 4.7$. With no wall the ideal MHD β_N limits for n=1, 2 and 3 are 2.7, 3.6, and 4.0, respectively. With a wall located at b/a = 1.35 on the outboard side only, the ideal MHD β_N limits for n=1, 2 and 3 are 6.1, 5.3, and 5.1, respectively. Calculations show that feedback coils, located near the front face of the shield plug in every other mid-plane port, could stabilize the n=1 resistive wall mode (RWM) up to 80-90% of the "with-wall" limit. The analysis of the RWM stabilization is benefiting from the experimental progress on DIII-D. The plasma configurations targeted have safety factor values above 2.0 everywhere, so that the (5,2) and (3,1) are the lowest order neoclassical tearing modes (NTMs) of interest. Stabilization of the NTMs using electron cyclotron current drive (ECCD) from the low field side at the toroidal field of 6.5 T would require frequencies of 140-170 GHz, which is close to the range of achieved values in the high-power long-pulse gyrotron R&D program. The LHCD system could also be used to launch two spectra, one for bulk CD and the other for NTM suppression.

H-Mode Operating Space: A wide range of H-mode plasmas have been examined using a global systems analysis code. The major and minor radius, and elongation, triangularity and aspect ratio are fixed at the reference ELMy H-mode inductively driven design point; R=2.14 m, a=0.595 m, κ(Xpt)=2.0, δ(Xpt)=0.7, A=3.6. The analysis used for operating point calculations incorporated plasma power and particle balance, in addition to several other global parameter relations. .In particular, the ITER98(y,2) scaling is assumed for the global energy confinement time. The plasmas considered spanned the ranges: $5 \le Q \le 30$, $5 \le P_{aux}$ (MW) ≤ 30, $1.05 \le n(0)/\langle n \rangle \le 1.25$, $0.3 \le n/n_{Gr} \le 1$,and $1.5 \le \beta_N \le 3$. In addition, the impurity concentrations in the plasma core were varied over 1 to 3% for Be and 0.0 to 0.3% for Ar, allowing higher radiated power fractions to more optimally distribute the exhaust power. Viable solutions must be within the engineering limits set by the heating of the cryogenically cooled toroidal field coils, stresses due to nuclear heating of the vacuum vessel, a temperature limit of 600 °C for the first wall Be tiles, particle power to the outboard divertor (<28 MW), and the radiated power load on the divertor and baffle (<6 - 8 MWm^{-2}). Increasing the radiated power in the divertor reduced the particle heat load and expanded the operating space significantly. For most H-mode plasmas at 10T, the TF coil limited the plasma duration to 20 s, which is 2 τ_{cr}, for the reference operating point and is the same as the reference ITER H-mode duration. The nominal operating point, shown as the circle at 150 MW with a 20 s flattop (Fig. 1), has significant margin to handle increased fusion power. If plasmas up to the no-wall stability limit of $\beta_N \approx 3$ can be attained, fusion power levels of 350 MW could be sustained for 10 s. High Q (= 15 - 30) operation could be attained for cases with low impurity content (1-2% Be), modest density peaking $n(0)/\langle n \rangle = 1.25$, n/n_{Gr} (0.7 – 1.0) and H98 (1.03 - 1.1).

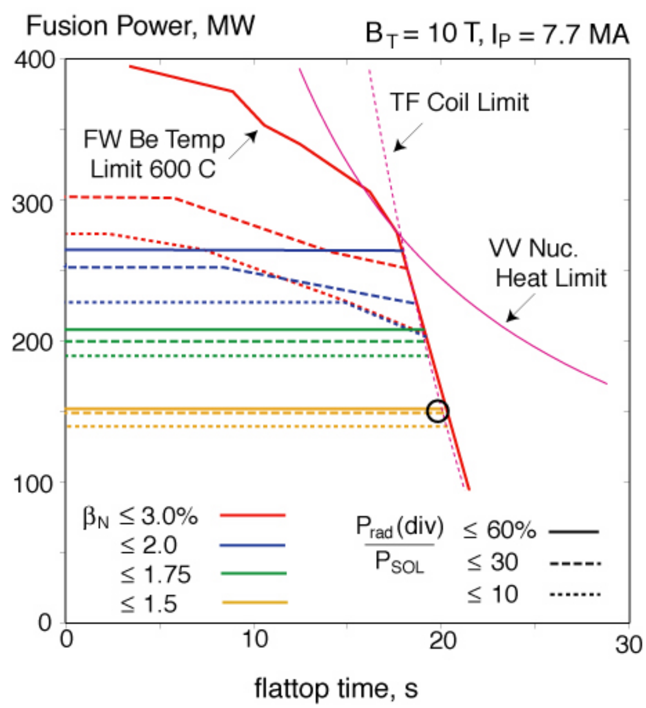


Fig. 1. H-Mode Operating Space in FIRE

AT Mode Operating Space: A similar global analysis has been used to determine the operating space for 100% non-inductive advanced tokamak modes in FIRE. An expression for the bootstrap current fraction is included and the current drive power is given by $P_{cd} = [nRI_p(1-f_{bs})]/\eta_{cd}$. The on-axis current drive is fixed at 200 kA from ICRF/FW, so that LHCD must make up any current not driven by the bootstrap effect. The current drive efficiency used in these scans is ηcd = 0.2 and 0.16 A/W-m^2 for ICRF/FW and LH, respectively, and is based on detailed

LH and ICRF/FW analysis for FIRE. The operating space was scanned for cases with Q = 5, at B_t = 6.5T, P_{LH} (MW) ≤ 30, P_{ICRF} (MW) ≤ 30, 1.05 ≤ n(0)/⟨n⟩ ≤ 2, 2 ≤ T(0)/⟨T⟩ ≤ 3, 0.3 ≤ n/n_{Gr} ≤ 1, 3.25 ≤ q_{95} ≤ 5, and 3 ≤ β_N ≤ 4.5. Attainment of β_N ≥ 3 will require feedback stabilization of the resistive wall modes (RWM). In addition, the impurity concentrations are varied over 1 to 3% for Be and 0.0 to 0.3% for Ar, allowing higher radiated power fractions. The operating space can be expanded by increasing Ar in the plasma to radiate more power in the divertor and on the first wall resulting in 1.5 ≤ Z_{eff} ≤ 2.3. The fraction of power radiated in the divertor (P_{rad}(div)) to power exhausted into the scrape-off layer (P_{SOL}) was allowed to vary from 10%, 30% and 60%. The same power handling limits were imposed as for the H-mode described above. The nominal operating point has 150 MW of fusion power for 32 s flattop. The flattop burn times for these AT plasmas are limited primarily by the nuclear heating in the vacuum vessel rather than TF coil heating. Imposing these constraints, the system study found that FIRE could attain high-β high-bootstrap AT plasmas with near steady-state conditions for up to 5 τ_{CR} as shown in Fig. 2. If the vacuum vessel/ shield was modified to withstand the nuclear heating induced stresses, the reference AT pulse length could be extended to ≈ 50 s (5 - 6 τ_{CR}). These Q = 5 plasmas require confinement corresponding to H98(y,2) ranging from 1.4 – 1.8 similar to those required in ITER. At the higher ranges of confinement, H98(y,2) = 1.6 – 2.0, Q = 10 plasmas are produced that have a reduced duration of 1-3 τ_{CR}.

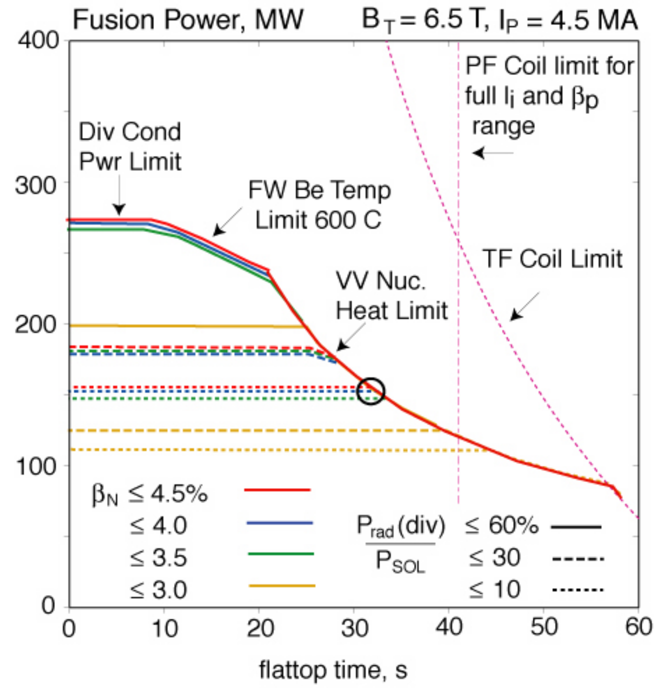


Fig. 2. AT Mode Operating Space in FIRE

Computer Simulation of Burning Plasma Phenomena

The rapid growth in computing power is enabling more realistic simulations of complex plasma phenomena. The Scientific Discovery through Advanced Computing Program (SciDAC). simulations of steady-state high-beta Advanced Tokamak plasma discharges with 100% non-inductive current composed of fast-wave, lower-hybrid, and bootstrap currents that are sustained for ≈ 4τ_{CR} have been done for FIRE using the Tokamak Simulation Code. This is accomplished by programming the heating and current-drive sources so that the inductive contribution to the plasma current is reduced to zero by the end of the ramp up and the current profile is that desired for AT operation. The simulations then confirm that the current profile remains unchanged for the flat top portion (≈ 4τ_{CR}) of the pulse. A simulation of the plasma response to a perturbation in the current profile (Fig. 3) produced by a drop in the lower hybrid current drive shows that the plasma duration is sufficient to study the evolution of a fusion dominated plasma on the current evolution time scale.

FIRE Engineering Activities

The FIRE engineering design was reviewed in detail at Snowmass, and the assessment team found that there were no feasibility issues with respect to the construction of FIRE. It was noted that the FIRE magnet design has the least complex magnet structure of the three proposed burning plasma experiments, and increased complexity often leads to decreased reliability. FIRE provided a detailed project cost estimate based upon industrial vendor and in-house quotes. The FIRE total project cost estimate of $1.186B (FY 2002) including 25% contingency was found to be reasonable by the Snowmass Assessment team. The cost estimate of the tokamak assembly (everything inside the cryogenic dewar) is $280 M without contingency.

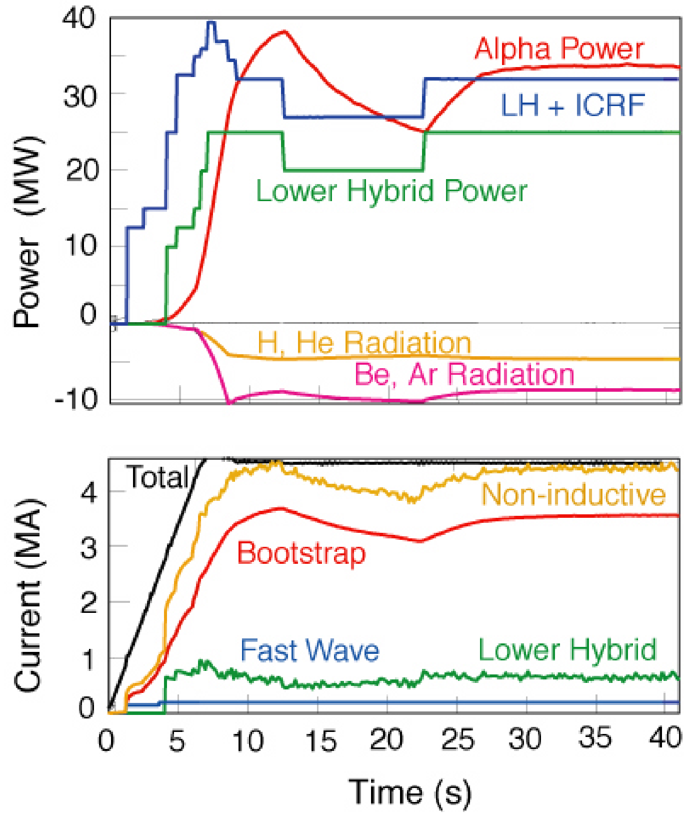


Fig. 3 response of Current Profile to Perturbation

There were a number of technical issues identified at the Snowmass meeting that will require additional work including: power handling during ELMs and disruptions, verify LH capability for neoclassical tearing mode stabilization, increased AT capability and pulse length, and pulse repetition rate. FIRE has modified the design of the toroidal field coils to include a second cooling tube that would increase the repetition rate to once per hour at full field and pulse length. Several approaches are being investigated to increase the number of pulses (total fusion energy yield) including a Small Business Innovative Research Program (SBIR) to develop improved inorganic magnet insulation that would be compatible with fusion reactor requirements. The operating space for AT plasmas has been established showing that up to 5 τ_{CR} can be accessed within the engineering limitations of the device. Improved disruption calculations and minor modifications to divertor/vacuum vessel support show that the FIRE vacuum vessel and divertor hardware can withstand plasma disruptions.

FIRE Outreach Program

FIRE continued its proactive outreach program with 14 presentations at fusion institutions and meetings, active participation in the International Tokamak Physics Activity (ITPA) , the APS spring meeting, the APS DPP, the 18th Symposium on Fusion Engineering (8 papers), 30th European Physical Society Conference on Plasma Physics and Controlled Fusion and the 19th IAEA Fusion Energy Conference. In addition, the FIRE web site was maintained as a site of FIRE documentation and information for the fusion program.

Work supported by DOE contract DE-AC02-76CH03073