Laboratories are Needed to Explore, Explain, and Expand the Frontiers of Science.

CHANDRA  
VLBA  
NIF  
NSO  
HST (NGST)  
SNS  
APS
Exploring the Frontiers of Burning Plasma Science

Dale M. Meade
for the FIRE Team

Presented at
19th IEEE/NPSS Symposium on Fusion Engineering (SOFE)
Atlantic City, NJ

January 22, 2001

http://fire.pppl.gov
Outline

- Objectives for a Next Step Experiment in Magnetic Fusion
- Burning Plasma Performance Considerations
- Compact High Field Approach - General Parameters
- Advanced Tokamak Longer Pulse Possibilities
- Summary
Is an Opportunity Emerging for Fusion?

(to DOE Lab Directors and DOE)
“I would add to this list two priorities that deserve special mention. The first involves the unique technological contribution we can make to our energy and national security by finding new sources of energy. Whether it is fusion or a hydrogen economy, or ideas that we have not yet explored, I believe we need to leapfrog the status quo and prepare for a future that, under any scenario, requires a revolution in how we find, produce and deliver energy.”

“I intend, therefore, that this Department take a leadership role in exploring how we can identify and use potentially abundant new sources of energy with dramatic environmental benefits.”

Federal Reserve Chairman Greenspan - On Energy Supply – Nov. 13, 2001
(Rice University)
“In the more distant future remains the potential of fusion power. A significant breakthrough in this area has been sought for years but seems discouragingly beyond reach. But success could provide a major contribution to our nation's future power needs. The input costs of fusion power would be minor, and it produces negligible nuclear waste or pollutants.”

What should we do to be ready?
Activities to Assess Next Steps in MFE

• Energy Authorization Bill (HR 4) passed by the House on August 1, 2001

  1. Calls for strengthening the base fusion sciences program

  2. directs DOE to submit a plan for a U.S. Burning Plasma Experiment to Congress by July 2004. In addition, DOE may also develop a plan for United States participation in an international burning plasma experiment for the same purpose, if it is highly likely to be constructed and cost-effective

• Fusion Energy Sciences Advisory Committee (FESAC) endorses recommendations of FESAC Burning Plasma Panel for Proactive BP Program.

• National Academy of Science is preparing a proposal to review burning plasma physics as required by HR 4 and recommended by FESAC.

• Preparations are beginning for a Snowmass Summer Study 2002 that will emphasize burning plasmas. International participation is encouraged.

Full text on  http://fire.pppl.gov
Is Fusion a Possible Energy Source?

• Fusion would be an ideal long term energy source – the natural energy source

• “Fusion, energy of the future, always has been, always will be.”

• How much will it cost to find out?

  Spent ~$10B on MFE in the U.S. during the past 50 years.

• What must be done to make a convincing case?

  Address the critics
Critical Issues to be Addressed in the Next Stage of Fusion Research

• **Burning Plasma Physics**
  - strong nonlinear coupling inherent in a fusion dominated plasma
  - access, explore and understand fusion dominated plasmas

• **Advanced Toroidal Physics**
  - develop and test physics needed for an attractive MFE reactor
  - couple with burning plasma physics

• **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

• **Neutron Resistant Materials** (separate facility)
  - high fluence testing using “point”neutron source

• Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives

• Nuclear Component Testing should wait for the correct reactor materials
One Step to Two DEMOs\textsuperscript{1, 2}

Second Phase
Scientific Feasibility

Three Large Tokamaks
JT-60 U
JET
TFTR

Third Phase
ITER Project
Tokamak Experimental Reactor

Choice of Concept

Fourth Phase
Electric Power Feasibility

Commercialization Phase
Economic Feasibility

Commercial Prototype

Three Large Tokamaks
JT-60 U
JET
TFTR

Scientific Foundation

Non-Tokamak
LHD, W 7X

Technology Demonstration

Scientific Foundation

2. European Plan Airaghi Report, May 2000

Even the first Director of ITER recommended against this strategy.
The Multi-Machine Strategy for Magnetic Fusion

Second Phase
Scientific Feasibility

Three Large Tokamaks
JT-60 U
JET
TFTR

Third Phase
Burning Plasma Scientific Base

International Program
Burning D-T
Adv. Long Pulse D-D
Materials Develop

Choice of Configuration

Fourth Phase
Electric Power Feasibility

Commercialization Phase
Economic Feasibility

Advanced DEMO
Attractive Commercial Prototype

Technology Demonstration
Tokamak burning plasma infrastructure could also provide facility to test non-tokamak configurations.

Non-Tokamak Configurations
Long Pulse Adv. Stellarator
Spherical Torus, RFP
Spheromak, FRC, MTF

Scientific Foundation

1985 2005 2020 2050

Reduced Technical Risk
Streamlined Management Structure
Better Product/Lower Overall Cost

Increased Technical Flexibility
Faster Implementation

(The overall Multi-Machine Strategy includes IFE)
Next Step Option (FIRE) Program Advisory Committee

- **Members:** Tony Taylor (Chair), Gerald Navratil, Ray Fonck, David Gates, Dave Hill, Wayne Houlberg, Tom Jarboe, Mitsuro Kikuchi, Earl Marmar, Raffi Nazikian, Craig Petty, Rene Raffray, Paul Thomas, James VanDam

- **Meetings**
  - July 20-21, 2000 at General Atomics, San Diego, CA.
  - January 17-18, 2001 at MIT, Cambridge, MA
  - July 10-11, 2001 at Univ. Wisc, Madison, WI
  - November 29-30 at LLNL, Livermore, CA

- **Charge for First and Second meetings**
  - Scientific value of a Burning Plasma experiment
  - Scientific readiness to proceed with such an experiment
  - Is the FIRE mission scientifically appropriate?
  - Is the initial FIRE design point optimal?

- Extensive PAC Reports provide detailed recommendations for the FIRE activity to address. NSO-PAC reports are on FIRE (http://fire.pppl.gov), will discuss in more detail under FY 2001-03 Plans.

**FIRE Study is a Pre-Conceptual design, integrated costs (1998-2002) <$12M.**
Fusion Science Objectives for a Major Next Step Burning Plasma Experiment

Explore and understand the strong non-linear coupling that is fundamental to fusion-dominated plasma behavior (self-organization)

- Energy and particle transport (extend confinement predictability)
- Macroscopic stability (β-limit, wall stabilization, NTMs)
- Wave-particle interactions (fast alpha particle driven effects)
- Plasma boundary (density limit, power and particle flow)
- Test/Develop techniques to control and optimize fusion-dominated plasmas.
- Sustain fusion-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macro stability, transport barriers and energetic particle modes.
- Explore and understand various advanced operating modes and configurations in fusion-dominated plasmas to provide generic knowledge for fusion and non-fusion plasma science, and to provide a foundation for attractive fusion applications.
Advanced Burning Plasma Exp't Requirements

**Burning Plasma Physics**

\[ Q \geq 5, \quad \sim 10 \text{ as target, ignition not precluded} \]

\[ f_\alpha = \frac{P_\alpha}{P_{\text{heat}}} \geq 50\%, \quad \sim 66\% \text{ as target, up to } 83\% \text{ at } Q = 25 \]

TAE/EPM stable at nominal point, able to access unstable

**Advanced Toroidal Physics**

\[ f_{bs} = \frac{I_{bs}}{I_p} \geq 50\% \quad \text{up to } 75\% \]

\[ \beta_N \sim 2.5, \text{ no wall} \quad \sim 3.6, \; n = 1 \text{ wall stabilized} \]

**Quasi-stationary**

Pressure profile evolution and burn control \( > 10 \tau_E \)

Alpha ash accumulation/pumping \( > \text{several } \tau_{\text{He}} \)

Plasma current profile evolution \( 1 \text{ to } 3 \tau_{\text{skin}} \)

Divertor pumping and heat removal \( \text{several } \tau_{\text{divertor}}, \tau_{\text{first wall}} \)
Optimization of a Burning Plasma Experiment

- Consider an inductively driven tokamak with copper alloy TF and PF coils precooled to LN temperature that warm up adiabatically during the pulse.

- Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.

What is the optimum for advanced steady-state modes?
### Fusion Ignition Research Experiment (FIRE)

http://fire.pppl.gov

<table>
<thead>
<tr>
<th>Design Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>• $R = 2.14 \text{ m}, \ a = 0.595 \text{ m}$</td>
</tr>
<tr>
<td>• $B = 10 \text{ T}$</td>
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<tr>
<td>• $W_{\text{mag}} = 5.2 \text{ GJ}$</td>
</tr>
<tr>
<td>• $I_p = 7.7 \text{ MA}$</td>
</tr>
<tr>
<td>• $P_{\text{aux}} \leq 20 \text{ MW}$</td>
</tr>
<tr>
<td>• $Q \approx 10$, $P_{\text{fusion}} \sim 150 \text{ MW}$</td>
</tr>
<tr>
<td>• Burn Time $\approx 20 \text{ s}$</td>
</tr>
<tr>
<td>• Tokamak Cost $\approx 375 \text{M (FY99)}$</td>
</tr>
<tr>
<td>• Total Project Cost $\approx 1.2 \text{B}$ at Green Field site.</td>
</tr>
</tbody>
</table>

**Mission:**
Attain, explore, understand and optimize fusion-dominated plasmas.

CIT + TPX = FIRE
FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters

\[
\omega_c \tau = B \tau \\
\rho^* = \rho/a \\
\nu^* = \nu_c/\nu_b \\
\beta 
\]

Similarity Parameter

\[
B R^{5/4} 
\]

Kadomtsev, 1975
Guidelines for Estimating Plasma Performance

Confinement (Elmy H-mode) - ITER98(y,2) based on today's data base

\[
\tau_E = 0.144 I^{0.93} R^{1.39} a^{0.58} n_{20}^{0.41} B^{0.15} A_i^{0.19} \kappa^{0.78} P_{\text{heat}}^{-0.69} \text{H(y,2)}
\]

Density Limit - Based on today's tokamak data base

\[
n_{20} \leq 0.8 \ n_{\text{GW}} = 0.8 \frac{I_p}{\pi a^2},
\]

Beta Limit - theory and tokamak data base

\[
\beta \leq \beta_N(I_p/aB), \quad \beta_N < 2.5 \text{ conventional, } \beta_N \sim 4 \text{ advanced}
\]

H-Mode Power Threshold - Based on today's tokamak data base

\[
P_{\text{th}} \geq (2.84/Ai) n_{20}^{0.58} B^{0.82} Ra^{0.81}, \text{ same as ITER-FEAT}
\]

Helium Ash Confinement \( \tau_{\text{He}} = 5 \ \tau_E \), impurities = 3% Be, 0% W

Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in alpha-dominated fusion plasmas is needed to confirm and extend the science basis.
FIRE’s Operating Density and Triangularity are Near the Optimum for the Elmy H-Mode

- The optimum density for the H-Mode is \( n/n_{GW} \approx 0.6 - 0.7 \)
- H-mode confinement increases with \( \delta \)
  - \( \delta \approx 0.7 \) FIRE
  - \( \delta \approx 0.5 \) ITER-FEAT
- Elm size is reduced for \( \delta > 0.5 \)
- \( Z_{eff} \) decreases with density (Mathews/ITER scaling)
- DN versus SN? C-Mod Exp'ts

Ongena et al, JET Results EPS 2001

Cordey et al, \( H = function (\delta, n/n_{GW}, n(0)/<n>) \) EPS 2001
Projections to FIRE Compared to Envisioned Reactors

ARIES-AT, Najmabadi, $Q = 50$

FIRST “ITER” Reactor
Toschi et al

FIRE
10T, 7.7MA, $R = 2.14m$, $A = 3.6$
1.7 $\tau_{\text{skin}}$

$P_{\text{fusion}} = 150$ MW
$n/n_{GW} = 0.7$

$\triangle$ $n(0)/<n>_{V} = 1.5$

$\times$ $n(0)/<n>_{V} = 1.2$

JET H-Mode**, Data Base
Physics Based Transport Model

GLF23 Transport Model With Real Geometry
ExB Shear Shows Improved Agreement With L- and H-mode and ITB Profile Database

Statistics computed incremental stored energy (subtracting pedestal region) using exactly same model used for ITB simulations

\[ \sigma_{RMS} = 13.0\% \]

97 discharges
DIII-D, JET, TFTR
L-, H-mode, ITB

* \( T_e, T_i, v_\phi \) predicted for ITBs
### Pedestal Temperature Requirements for Q=10

<table>
<thead>
<tr>
<th>Device</th>
<th>Flat ne*</th>
<th>Peaked ne*</th>
<th>Peaked ne w/ reversed q</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGNITOR</td>
<td>5.1</td>
<td>5.0</td>
<td>5.1</td>
</tr>
<tr>
<td>FIRE</td>
<td>4.1</td>
<td>4.0</td>
<td>3.4</td>
</tr>
<tr>
<td>ITER-FEAT‡</td>
<td>5.8</td>
<td>5.6</td>
<td>5.4</td>
</tr>
</tbody>
</table>

* flat density cases have monotonic safety factor profile

* $n_{eo}/n_{ped} = 1.5$ with $n_{ped}$ held fixed from flat density case

❖ 10 MW auxiliary heating

❖ 11.4 MW auxiliary heating

❖ 50 MW auxiliary heating

Need a model for the pedestal temperature, FIRE has the advantage of highest triangularity and low density $n/n_{GW} = 0.6 - 0.7$
GLF23 Predicts an Internal Transport Barrier in FIRE as a Result of Shafranov-Shift Stabilization of the ITG Mode

- **Barrier only forms if some density peaking is present.**
- **Diamagnetic component of ExB shear helps after ITB is formed.**

Reactor relevant
no beam rotation
1 1/2-D Simulation of Burn Control in FIRE* (TSC)

- ITER98(y,2) scaling with $H(y,2) = 1.1$, $n(0)/<n> = 1.2$, and $n/n_{GW} = 0.67$
- Burn Time $\approx 20$ s $\approx 21 \tau_E \approx 4 \tau_{He} \approx 2 \tau_{skin}$

$Q = \text{Pfusion}/(\text{Paux} + \text{Poh})$
TSC Simulation of a “Fusion Dominated” Plasma

8.5 T, 5.4 MA, t(flattop) = 32 s

- $H(y,2) = 1.6$
- $\beta_N = 3.5$
- $n(0)/\langle n \rangle = 1.5$

$Q = 7.8$, $f_\alpha = 61\%$

$f_{BS} = 65\%$
Contributors to the FIRE Engineering Design Study

FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

Advanced Energy Systems
Argonne National Laboratory
DAD Associates
General Atomics Technology
Georgia Institute of Technology
Idaho National Engineering Laboratory
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Sandia National Laboratory
Stone and Webster
The Boeing Company
University of Illinois
University of Wisconsin
FIRE Incorporates Advanced Tokamak Innovations

AT Features
- DN divertor
- strong shaping
- very low ripple < 0.3%
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports

**Wedged TF Coils** (16), 15 plates/coil*
Inner Leg BeCu C17510, remainder OFHC C10200

Compressio Ring
Double Wall Vacuum Vessel (316 S/S)
All PF and CS Coils* OFHC C10200
Internal Shielding (60% steel & 40% water)
Vertical Feedback andError Field Correction Coils
Passive Stabilizer Plates space for wall mode stabilizers
W-pin Outer Divertor Plate Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

FIRE Cross/Persp- 5/25//DOE
### Basic Parameters and Features of FIRE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, major radius</td>
<td>2.14 m</td>
</tr>
<tr>
<td>a, minor radius</td>
<td>0.595 m</td>
</tr>
<tr>
<td>κx, κ95</td>
<td>2.0, 1.77</td>
</tr>
<tr>
<td>δx, δ95</td>
<td>0.7, 0.55(AT) - 0.4(OH)</td>
</tr>
<tr>
<td>q95, safety factor at 95% flux surface</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Bt, toroidal magnetic field</td>
<td>10 T with 16 coils, 0.3% ripple @ Outer MP</td>
</tr>
<tr>
<td>Toroidal magnet energy</td>
<td>5.8 GJ</td>
</tr>
<tr>
<td>Ip, plasma current</td>
<td>7.7 MA</td>
</tr>
<tr>
<td>Magnetic field flat top, burn time</td>
<td>28 s at 10 T in dd, 20 s @ Pdt ~ 150 MW</td>
</tr>
<tr>
<td>Pulse repetition time</td>
<td>~3 hr @ full field and full pulse length</td>
</tr>
<tr>
<td>ICRF heating power, maximum</td>
<td>20 MW, 100 MHz for 2Ωr, 4 mid-plane ports</td>
</tr>
<tr>
<td>Neutral beam heating</td>
<td>Upgrade for edge rotation, CD - 120 keV PNBI?</td>
</tr>
<tr>
<td>Lower Hybrid Current Drive</td>
<td>Upgrade for AT-CD phase, ~20 MW, 5.6 GHz</td>
</tr>
<tr>
<td>Plasma fueling</td>
<td>Pellet injection (≥2.5 km/s vertical launch inside mag axis, guided slower speed pellets)</td>
</tr>
<tr>
<td>First wall materials</td>
<td>Be tiles, no carbon</td>
</tr>
<tr>
<td>First wall cooling</td>
<td>Conduction cooled to water cooled Cu plates</td>
</tr>
<tr>
<td>Divertor configuration</td>
<td>Double null, fixed X point, detached mode</td>
</tr>
<tr>
<td>Divertor plate</td>
<td>W rods on Cu backing plate (ITER R&amp;D)</td>
</tr>
<tr>
<td>Divertor plate cooling</td>
<td>Inner plate-conduction, outer plate/baffle- water</td>
</tr>
<tr>
<td>Fusion Power/ Fusion Power Density</td>
<td>150 - 200 MW, ~6 -8 MW m-3 in plasma</td>
</tr>
<tr>
<td>Neutron wall loading</td>
<td>~ 2.3 MW m-2</td>
</tr>
<tr>
<td>Lifetime Fusion Production</td>
<td>5 TJ (BPX had 6.5 TJ)</td>
</tr>
<tr>
<td>Total pulses at full field/power</td>
<td>3,000 (same as BPX), 30,000 at 2/3 Bt and Ip</td>
</tr>
<tr>
<td>Tritium site inventory</td>
<td>Goal &lt; 30 g, Category 3, Low Hazard Nuclear Facility</td>
</tr>
</tbody>
</table>
TF coils are being Designed with Added Margin.

- **FIRE* Baseline**
  
  \[ R = 2.14 \text{ m}, \quad a = 0.595 \text{ m} \]
  
  \[ B = 10 \text{ T}, \quad I_p = 7.7 \text{ MA}, \]
  
  \[ 20 \text{ s flat top}, \quad P_{\text{fus}} = 150 \text{ MW} \]

- **Wedged TF/compression ring**
  
  BeCu (C17510) inner leg

- **The peak conductor VM Stress** of 529 MPa for 10 T (7.7 MA) is within the static allowable stress of 724 MPa
  
  \( \text{(Allowable/Calculated} = 1.3 \)
TF Conductor Material for FIRE is “Essentially” Available

- BeCu alloy C 17510 - 68% IACS is now a commercial product for Brush Wellman.

- A relatively small R&D program is needed to assure that the plates will be available in the properties and sizes required.

The plate on the right was manufactured for BPX.
Edge Physics and PFC Technology: Critical Issue for Fusion

Plasma Power and particle Handling under relevant conditions
   Normal Operation / Off Normal events

Tritium Inventory Control
   must maintain low T inventory in the vessel ⇒ all metal PFCs

Efficient particle Fueling
   pellet injection needed for deep and tritium efficient fueling

Helium Ash Removal
   need close coupled He pumping

Non-linear Coupling with Core plasma Performance
   nearly every advancement in confinement can be traced to the edge
   Edge Pedestal models first introduced in ~ 1992 first step in understanding
   Core plasma (low $n_{\text{edge}}$) and divertor (high $n_{\text{edge}}$) requirements conflict

Solutions to these issues would be a major output from a next step experiment.
FIRE is being Designed to Test the Physics and In-Vessel Technologies for ARIES-RS

<table>
<thead>
<tr>
<th></th>
<th>JET</th>
<th>FIRE</th>
<th>ARIES-RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Power Density (MW/m³)</td>
<td>0.2</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>Neutron Wall Loading (MW/m²)</td>
<td>0.2</td>
<td>2.3</td>
<td>4</td>
</tr>
<tr>
<td>Divertor Challenge (Pheat/NR)</td>
<td>~5</td>
<td>~10</td>
<td>~35</td>
</tr>
<tr>
<td>Power Density on Div Plate (MW/m²)</td>
<td>3</td>
<td>~15-19 → 6</td>
<td>~5</td>
</tr>
<tr>
<td>Burn Duration (s)</td>
<td>4</td>
<td>20</td>
<td>steady</td>
</tr>
</tbody>
</table>
FIRE's Divertor can Handle Attached (<25 MW/m²) and Detached (5 MW/m²) Operation

Reference Design is semi-detached operation with <15 MW/m².
Carbon targets used in most experiments today are not compatible with tritium inventory requirements of fusion reactors.
FIRE In-Vessel Remote Handling System

**In-vessel transporter**
- Articulated boom deployed from sealed cask
- Complete in-vessel coverage from 4 midplane ports
- Fitted with different end-effector depending on component to be handled
- First wall module end-effector shown

**Divertor end-effector**
- High capacity (module wt. ~ 800 kg)
- Four positioning degrees of freedom
- Positioning accuracy of millimeters required
## Potential Next Step Burning Plasma Experiments

<table>
<thead>
<tr>
<th>Cost Drivers</th>
<th>IGNITOR</th>
<th>FIRE</th>
<th>JET U</th>
<th>PCAST</th>
<th>ARIES-RS</th>
<th>ITER-FEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Volume (m³)</td>
<td>11</td>
<td>27</td>
<td>108</td>
<td>390</td>
<td>350</td>
<td>828</td>
</tr>
<tr>
<td>Plasma Surface (m²)</td>
<td>36</td>
<td>60</td>
<td>160</td>
<td>420</td>
<td>420</td>
<td>610</td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>12</td>
<td>7.7</td>
<td>6</td>
<td>15</td>
<td>11.3</td>
<td>15</td>
</tr>
<tr>
<td>Magnet Energy (GJ)</td>
<td>5</td>
<td>5</td>
<td>1.6</td>
<td>40</td>
<td>85</td>
<td>50</td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td>100</td>
<td>150</td>
<td>30</td>
<td>400</td>
<td>2170</td>
<td>400</td>
</tr>
<tr>
<td>Burn Duration (s), inductive</td>
<td>~1</td>
<td>20</td>
<td>10</td>
<td>120</td>
<td>steady</td>
<td>400</td>
</tr>
<tr>
<td>( \tau ) Burn/( \tau ) CR</td>
<td>~2</td>
<td>0.6</td>
<td>1</td>
<td>steady</td>
<td>2</td>
<td></td>
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<tr>
<td>Cost Estimate ($B-2000$)</td>
<td>1.2</td>
<td>~0.6</td>
<td>6.7</td>
<td>10.6*</td>
<td>4.6</td>
<td></td>
</tr>
</tbody>
</table>

* first, \$5.3\ B for 10th of a kind

AR RS/ITERS/PCAST/FIRE/IGN
<table>
<thead>
<tr>
<th>CY</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
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<tr>
<td>Community Outreach and Involvement</td>
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<tr>
<td>FESAC Recommendations on Burning Plasmas August 2, 2001</td>
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<td>NSO Assessment</td>
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<tr>
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Illustrative Schedule for U.S. Burning Plasma Experiment

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- **CD-0**, Approve Mission Need and Initiate Preproject planning activities.
- **CD-1**, Approve Preliminary Range
- **CD-2**, Approve Performance Baseline
  - (Baseline cost and schedule are “locked.” Project included in budget submission.)
- **CD-3**, Approve Start of Construction
- **CD-4**, Approve Start of Ops
  - Operations

- **ITER-EDA Extension Complete**
- **Pre-Conceptual Design**
- **Conceptual Design**
- **Preliminary Design**
- **Final Design**
- **Physics Validation**
- **Prepare Documentation**

Jan 28, 2000
• Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for $\geq 15$ years.

• Compact High-Field Tokamak Burning Plasma Experiment(s) would be a natural extension of the ongoing “advanced” tokamak program and could begin alpha-dominated experiments by $\sim 10$ years.

• More than one high gain burning plasma facility is needed in the world program.

• The Snowmass 2002 Summer Study will provide a forum to assessing approaches. The NRC Review in 2002 will assess contributions to broader science issues.
Summary

• A Window of Opportunity may be opening for U.S. Energy R&D. We should be ready. The Modular or Multi-Machine Strategy has advantages for addressing the science and technology issues of fusion.

• FIRE with a construction cost ~ $1B, has the potential to:
  • address the important burning plasma issues, performance ~ ITER
  • investigate the strong non-linear coupling between BP and AT,
  • stimulate the development of reactor relevant PFC technology, and
  • provide generic BP science and possibly BP infrastructure for non-tokamak BP experiments in the U.S.

• Some areas that need additional work to realize this potential include:
  • Apply recent enhanced confinement and advanced modes to FIRE
  • Understand conditions for enhanced confinement regimes
  • Compare DN relative to SN - confinement, stability, divertor, etc
  • Complete disruption analysis, develop better disruption control/mitigation.

• If a positive decision is made in this year, FIRE is ready to begin Conceptual Design in FY2003 with target of first plasmas ~ 2010.

http://fire.pppl.gov
Additional FIRE Papers

PC-2-11 Fusion Ignition Research Experiment Machine Configuration Update. T. Brown

PC-2-12 Challenges for Plasma Diagnostics in a Next Step device (FIRE). K. Young

PC-2-13 Nuclear Considerations for FIRE. M. Sawan

PC-2-14 Design of Fusion Ignition Research Experiment (FIRE) Plasma Facing Components. M. Ulrickson

PC-2-15 Alternative Structural Concepts for the Fusion Ignition research Experiment (FIRE). P. Titus

OC-5-3 Engineering Status and Plans for FIRE. P. Heitzenroeder

OC-5-4 Advanced Tokamak Scenarios for the FIRE Burning Plasma Experiment. C. Kessel