Burning Plasma Physics - The Next Frontier

Three Options (same scale)

**FIRE**
US Based
International Modular Strategy

**ITER-FEAT**
JA, EU or CA Based
International Partnership

**IGNITOR**
Italian Based
International Collaboration
FIRE
A Next Step Option for Magnetic Fusion

Dale M. Meade
for the FIRE Team

Presented at
6th International Symposium on Fusion Nuclear Technology
San Diego, CA

April 10, 2002

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
Recent Activities Impacting a Next Step 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
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
The Multi-Machine Strategy for Magnetic Fusion

Second Phase
Scientific Feasibility

Three Large Tokamaks

JT-60 U
JET
TFTR

International Program

Burning Plasma
Scientific Base

Advanced DEMO
Non-Tokamak Configurations

Long Pulse Adv. Stellarator
Spherical Torus, RFP
Spheromak, FRC, MTF

Choice of Configuration

“ARIES”
Attractive Commercial Prototype

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

Fourth Phase
Electric Power Feasibility

Commercialization Phase
Economic Feasibility

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](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 ($\beta$-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

\[ f_{bs} = \frac{I_{bs}}{I_p} \geq 50\% \quad \text{up to } 75\% \]
\[ \beta_N \sim 2.5, \text{ no wall} \quad \sim 3.6, \text{ } n = 1 \text{ wall stabilized} \]

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.

Q = 10, $H = 1.1$, $n/nGW < 0.75$
$q_{cyl} = 3.0$, $\kappa > 1.8$,
$P_{aux} = 15$ MW, 20 s flat top for $B_T$, $I_p$

ITER98(y,2)
scaling
$n(0)/<n> = 1.2$

ITER - FEATFIRE
ARIES-RS (8T), ASSTR (11T)

What is the optimum for advanced steady-state modes?
**Fusion Ignition Research Experiment**

*(FIRE)*

http://fire.pppl.gov

### Design Features

- **R** = 2.14 m,  **a** = 0.595 m
- **B** = 10 T
- **$W_{mag}$** = 5.2 GJ
- **$I_p$** = 7.7 MA
- **$P_{aux}$** ≤ 20 MW
- **Q** ≈ 10, **$P_{fusion}$** ≈ 150 MW
- **Burn Time** ≈ 20 s
- **Tokamak Cost** ≈ $375M (FY99)
- **Total Project Cost** ≈ $1.2B at Green Field site.

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

**CIT + TPX = FIRE leading to ARIES**
FIRE is a Modest Extrapolation in Plasma Confinement

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

Dimensionless Parameters

<table>
<thead>
<tr>
<th>ITER-EDA</th>
<th>Q ~ 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER-FEAT</td>
<td>Q = 10</td>
</tr>
</tbody>
</table>

Similarity Parameter

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

Kadomtsev, 1975

\[ B\tau_{Eth} \sim \rho^{* -2.88} \beta^{-0.69} \nu^*{-0.08} \]
FIRE would Extend the Transport Understanding Toward ARIES

FIRE and ITER-FEAT calculated for $Q = 10$, $a/\rho_i$ evaluated at plasma center
Guidelines for Estimating Plasma Performance

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

$$\tau_E = 0.144 I^{0.93} R^{1.39} a^{0.58} n_0^{0.41} B^{0.15} A_i^{0.19} K^{0.78} P_{\text{heat}}^{-0.69} H(y,2)$$

Density Limit - Based on today's tokamak data base

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

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 $\tau_{He} = 5 \, \tau_E$, 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, \( H = \text{function (} \delta, n/n_{GW}, n(0)/<n>\) \) EPS 2001

FIRE H-Mode 4
1 1/2-D Simulation of Elmy H-Mode 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 \( \approx 20 \text{ s} \approx 21 \tau_E \approx 4 \tau_{He} \approx 2 \tau_{skin} \)

- \( Q = \frac{P_{\text{fusion}}}{P_{\text{aux}} + P_{\text{ohm}}} \)
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

\[ \sigma_{\text{RMS}} = 13.0\% \]
97 discharges
DIII-D, JET, TFTR
L-, H-mode, ITB

* \( T_e, T_i, \psi \)
predicted for ITBs

JJEK - BP2001
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
Simulation of Advanced Tokamak Regime in FIRE

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

H(y,2) = 1.6, \( \beta_N = 3.5 \), \( n(0)/<n> = 1.5 \)

\[ Q = 7.8, f_\alpha = 61\% \]

\[ f_{BS} = 65\% \]

Fusion Dominated Plasma
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 at ISFNT-6

FIRE Vacuum Vessel Design and Configuration
Brad Nelson P-1.VAC-2

FIRE, A Next Step Option for Magnetic Fusion
Dale Meade I-3.BPC-3

Plasma Heating and Current Drive Systems for the Fusion Ignition Research Experiment (FIRE)
David Swain P-3.BPC-1

Nuclear Features of the Fusion Ignition Research Experiment (FIRE)
Mohamed Sawan P-3.BPC-2

Physics Basis and Simulation of Burning Plasma Physics for the Fusion Ignition Research Experiment (FIRE)
Charles Kessel P-3.BPC-3

Engineering Overview of the Fusion Ignition Research Experiment (FIRE)
Richard Thome P-4.NSD-1

Design of the Fusion Ignition Research Experiment (FIRE) Plasma Facing Components
Dan Driemeyer P-4.FWC-19

Magnet Structural Design for the Fusion Ignition Research Experiment (Fire)
Peter Titus P-5.MAT-43
FIRE Incorporates Advanced Tokamak Features

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

**Diagram:**
- Wedged TF Coils (16), 15 plates/coil*
- Inner Leg BeCu C17510, remainder OFHC C10200
- Compression Ring
- Double Wall Vacuum Vessel (316 S/S)
- All PF and CS Coils* OFHC C10200
- Internal Shielding (60% steel & 40% water)
- Vertical Feedback and Error Field Correction Coils
- Passive Stabilizer Plates space for wall mode stabilizers
- W-pin Outer Divertor Plate Cu backing plate, actively cooled

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.
### Basic Parameters and Features of FIRE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</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>$\kappa_x$, $\kappa_{95}$</td>
<td>2.0, 1.77</td>
</tr>
<tr>
<td>$\delta_x$, $\delta_{95}$</td>
<td>0.7, 0.55(AT) - 0.4(OH)</td>
</tr>
<tr>
<td>q$_{95}$, safety factor at 95% flux surface</td>
<td>&gt;3</td>
</tr>
<tr>
<td>B$_t$, 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 2$\Omega_r$, 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 ($\geq$2.5 km/s vertical launch inside mag axis, guided slower speed pellets)</td>
</tr>
<tr>
<td>First wall materials</td>
<td>Be tiles, no carbon</td>
</tr>
<tr>
<td>First wall cooling</td>
<td>Conduction cooled to water cooled Cu plates</td>
</tr>
<tr>
<td>Divertor configuration</td>
<td>Double null, fixed X point, detached mode</td>
</tr>
<tr>
<td>Divertor plate</td>
<td>W rods on Cu backing plate (ITER R&amp;D)</td>
</tr>
<tr>
<td>Divertor plate cooling</td>
<td>Inner plate-conduction, outer plate/baffle- water</td>
</tr>
<tr>
<td>Fusion Power/ Fusion Power Density</td>
<td>150 - 200 MW, ~6 - 8 MW m$^{-3}$ in plasma</td>
</tr>
<tr>
<td>Neutron wall loading</td>
<td>$\sim$ 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>
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_{edge}) and divertor (high n_{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

FIRE

- B = 10 T
- R = 2.14 m
- Pfusion = ~ 150 MW
- Volume = 27 m³
- Fusion Power Density (MW/m³) = 0.2
- Neutron Wall Loading (MW/m²) = 0.2
- Divertor Challenge (Pheat/NR) = ~5
- Power Density on Div Plate (MW/m²) = 3
- Burn Duration (s) = 4

ARIES-RS The “Goal”

- B = 8 T
- R = 5.5 m
- Pfusion = 2170 MW
- Volume = 350 m³
- Fusion Power Density (MW/m³) = 6
- Neutron Wall Loading (MW/m²) = 4
- Divertor Challenge (Pheat/NR) = ~35
- Power Density on Div Plate (MW/m²) = ~15-19 → 6
- Burn Duration (s) = steady

- ~ 3X
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.
Divertor Module Components for FIRE

Sandia

Two W Brush Armor Configurations
Tested at 25 MW/m²

Finger Plate for Outer Divertor Module

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
Timetable for a Major Next Step in Magnetic Fusion

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**ITER Activities and Decisions**

- **ITER-EDA Complete**
- **Japan Site offer**
- **EU Site offer**
- **Preferred ITER Site Chosen**
- **ITER - Final Agreement Signed**
- **ITER Legal Entity**
- **ITER Construction Authorization**
- **Sixth European Framework Programme** Jan 1 2007

**US Activities and Decisions**

- **FESAC BP Recommendations**
- **Snowmass Assessment**
- **FESAC BP Strategy Panel**
- **National Academy Review**
- **DOE Decision CD-0**
- **DOE Response to Congress per HR-4/S-1766**

**U.S. Burning Plasma Design Activity - FIRE**

<table>
<thead>
<tr>
<th>Preconceptual Design</th>
<th>Response to Snowmass</th>
<th>Plan</th>
<th>Conceptual Design</th>
<th>Prelim. Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Plan</td>
<td>Conceptual Design</td>
<td>Prelim. Design</td>
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<tr>
<td></td>
<td></td>
<td>New Initiative in FY 2003?</td>
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</table>
The 2002 Fusion Summer Study will be a forum for the critical assessment of major next-steps in the fusion energy sciences program, and will provide crucial community input to the long range planning activities undertaken by the DOE and the FESAC. It will be an ideal place for a broad community of scientists to examine goals and proposed initiatives in burning plasma science in magnetic fusion energy and integrated research experiments in inertial fusion energy.

This meeting is open to every member of the fusion energy science community and significant international participation is encouraged.

**Objectives of the Fusion Summer Study:**

- Review scientific issues in burning plasmas to establish the basis for the following two objectives. Address the relation of burning plasma in tokamaks to innovative MFE confinement concepts and of ignition in IFE to integrated research facilities.

- Provide a forum for critical discussion and review of proposed MFE burning plasma experiments (e.g. IGNITOR, FIRE, and ITER) and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas.

- Provide a forum for the IFE community to present plans for prospective integrated research facilities, assess present status of the technical base for each, and establish a timetable and technical progress necessary to proceed for each.

**Background:** The 2002 Summer Study will build on earlier planning activity at the 1999 Fusion Summer Study and the scientific assessments at the UFA sponsored Burning Plasma Science Workshops (Austin, Dec 2000; San Diego, May 2001). The scientific views of the participants developed during the 2002 Summer Study preparation activities and during the 2002 Summer Study itself, will provide critical fusion community input to the decision process of FESAC and DOE in 2002-2003, and to the review of burning plasma science by the National Academy of Sciences called for by FESAC and Energy Legislation which was passed by the House of Representatives [H. R. 4].

**Output of the Fusion Summer Study:** An executive summary based on summary reports from each of the working groups will be prepared as well as a comprehensive proceedings of plenary and contributed presentations.

**Program Committee Co-Chairs:**

Roger Bangerter, Lawrence Berkeley National Laboratory
Gerald Navratil, Columbia University
Ned Sauthoff, Princeton University


[http://fire.pppl.gov](http://fire.pppl.gov)
• 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 \(~ 10\) 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.
### 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>
</tr>
<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 \text{ B for 10th of a kind}
MFE DEVELOPMENT PROGRAM

Core Program

Core Physics & Technology Program (Supporting all Areas)

TFTR

Q-1 DT

Burning Plasma Experiment

Des. Construction Burning Plasma & Self Heating

Engr. Test Reactor

EDA Construction

Materials Test Facility

Design Construction Reactor Materials Qualification

Steady State Experiment

Design Construction Physics & Technology of Steady State

Concept Improvement

Stellarator
Adv. Tokamak
Reverse Field Pinch
Compact Toroids

Concept Optimization

Demonstration Power Plant

Design Construction

Electric Power Prod.
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 a target of first plasmas ~ 2010.

http://fire.pppl.gov