Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science
FIRE
Exploring the Frontier of Fusion Science

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for the FIRE Team

Presented at
AST 558 - Seminar in Plasma Physics
PPPL

March 4, 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 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
The Grand Challenge, Science and Technology for Fusion

Key Plasma Performance Metrics
- Fusion Gain ($Q_p$)
- Fusion Energy Density
- Duty Cycle/Repetition Rate

Key Engineering Metrics
- First Wall Lifetime
- Availability/Reliability
- Environment and Safety
- System Costs
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 D-T
- Adv. Long Pulse D-D
- Materials Develop

Third Phase
Burning Plasma Scientific Base

Scientific Foundation

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

Fourth Phase
Electric Power Feasibility

Choice of Configuration

Commercialization Phase
Economic Feasibility

Advanced DEMO

Attractive Commercial Prototype

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

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)
Plasma Requirements for a Burning Plasma

Power Balance

\[ P_{\text{aux-heat}} + n^2 \langle \sigma v \rangle U_{\alpha} V_p/4 - C_B T^{1/2} n e^2 V_p = 3n k T V_p/\tau_E + d(3n k T V_p)/dt \]

where: \( n_D = n_T = n_e/2 = n/2 \), \( n^2 \langle \sigma v \rangle U_{\alpha} V_p/4 = P_{\alpha} \) is the alpha heating power, \( C_B T^{1/2} n_e^2 V_p \) is the radiation loss, \( W_p = 3n k T V_p \) and \( \tau_E = W_p/(P_{\text{aux-heat}} - dW_p/dt) \) is the energy confinement time.

In Steady-state:

\[
\begin{align*}
n \tau_E &= \frac{3kT}{\langle \sigma v \rangle U_{\alpha} (Q+5)/4Q - C_B T^{1/2}} \\
\end{align*}
\]

where \( Q = P_{\text{fusion}}/ P_{\text{aux-heat}} \)

\( Q = 1 \) is Plasma Breakeven, \( Q = \infty \) is Plasma Ignition
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**

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

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

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

**Advanced Toroidal Physics**

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

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

**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 \( \text{several } \tau_{\text{divertor}}, \tau_{\text{first wall}} \)
Stepping Stones for Resolving the Critical Fusion Plasma Science Issues for an Attractive MFE Reactor

Attractive MFE Reactor
(ARIES or A-SSTR)
Vision

Existing Data Base
Emerging Advanced Toroidal Data Base

Alpha Dominated
\[ f_\alpha = \frac{P_\alpha}{P_\alpha + P_{\text{ext}}} > 0.5, \]
\[ \tau_{\text{Burn}} > 15 \tau_E, 2 - 3 \tau_{\text{He}} \]

Burning Plasma Physics

Advanced Toroidal Physics (e.g., bootstrap fraction)

The Modular or Multi-Machine Strategy.
Guidelines for Estimating Plasma Performance

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

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

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.
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 \text{ MW}, 20 \text{ s flat top for } B_T, I_p

\tau_J = \text{ flat top time/ current redistribution time}

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

Design Features

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

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

CIT + TPX = FIRE
Three Options to Study Burning Plasma Physics

Three Options (same scale)

FIRE

ITER-FEAT

IGNITOR
FIRE is a Modest Extrapolation in Plasma Confinement

\[ \frac{\omega_c}{\tau} = \frac{B}{\tau} \]
\[ \rho^* = \frac{\rho}{a} \]
\[ \nu^* = \frac{\nu_c}{\nu_b} \]
\[ \beta \]

Dimensionless Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ITER-EDA, Q \sim 50</th>
<th>ITER-FEAT, Q = 10</th>
<th>FIRE, Q = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>\rho^*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>\nu^*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>\beta</td>
<td></td>
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</tr>
</tbody>
</table>

Similarity Parameter

\[ B \tau_{\text{Eth}} \sim \rho^{*-2.88} \beta^{-0.69} \nu^*^{-0.08} \]

Kadomtsev, 1975
Parameters for H-Modes in Potential Next Step D-T Plasmas

ITER-FEAT (15 MA): Q = 10, H = 0.95, FIRE*(7.7 MA): Q = 10, H = 1.03, JET-U (6 MA): Q = 0.64, H = 1.1
Guidelines for Estimating Plasma Performance

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

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

Density Limit - Based on today's tokamak data base

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Beta Limit - theory and tokamak data base

$$\beta \leq \beta_N(l_p/aB), \quad \beta_N < 2.5 \ \text{conventional}, \ \beta_N \sim 4 \ \text{advanced}$$

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

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
Projections to FIRE Compared to Envisioned Reactors

ARIES-AT, Najmabadi,

FIRST “ITER” Reactor
Toschi et al

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

\[ P_{\text{fusion}} = 150 \text{ MW} \]

\[ n/n_{GW} = 0.7 \]

\[ n(0)/<n>_V = 1.5 \]

\[ n(0)/<n>_V = 1.2 \]

JET H-Mode** Data Base

Q = 50
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

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

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

Q = 10
1 1/2-D Simulation of Burn Control in FIRE* (TSC)

R = 2.14m, A = 3.6, 10 T, 7.7 MA, ~20 s flat top

- 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}

\[ Q \approx 12 \]

Omega Power

Auxiliary Power

Ohmic Power

Q = \text{Pfusion}/(\text{Paux} + \text{Poh})
Normalized Burn Time (Plasma Skin Time)

Fusion Power (MW)

ITER-FEAT

Skin times

Power (MW)

FIRE*

Q ≈ 11.6

Power (MW)

IGNITOR

Q = 8.3

Waveforms from talks presented at UFA BPS Workshop 2
FIRE could Access the “Long Pulse” Advanced Tokamak Mode Frontier at Reduced Toroidal Field.

Note: FIRE is ≈ the same physical size as TPX and KSTAR. At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT. The Number of Skin Times curve assumes a constant skin time of 13s.

The main limit to long pulses is the divertor and first wall - a generic problem for magnetic fusion.
FIRE is Pursuing \textbf{Burning Advanced Tokamak Plasmas}

- High potential benefits of Advanced Tokamak operation make AT research mandatory on any Burning Plasma Experiment (\textit{Snowmass 1999})
- ARIES Power Plant studies show that AT plasmas provide
  - High $\beta$ ----> high fusion power density
  - Large bootstrap (self-driven) current and good alignment ----> low recirculating power
  - Good plasma confinement consistent with high $\beta$ and high bootstrap current ----> high fusion gain $Q$
  - \textbf{This combination drives down the machine size and the cost of electricity (COE)}
- \textbf{FIRE} must demonstrate that these plasmas can be established and maintained in a stationary state
FIRE Has Adopted the AT Features Identified by ARIES Studies

- High toroidal field
- Double null
- Strong shaping
  - $\kappa = 2.0$, $\delta = 0.7$
- Internal vertical position control coils
- Cu wall stabilizers for vertical and kink instabilities
- Very low ripple (0.3%)
- ICRF/FW on-axis CD
- LH off-axis CD
- LHCD stabilization of NTMs
- Tungsten divertor targets
- Feedback coil stabilization of RWMs
- Burn times exceeding current diffusion times
- Pumped divertor/pellet fueling/impurity control to optimize plasma edge
FIRE can Test Advanced Modes Used in Advanced Reactor Designs

\[ \frac{\beta}{(S\epsilon)} \]

\[ \epsilon \beta_p \]

\[ q^* = 2 \]

\[ q^* = 3 \]

\[ q^* = 4 \]

\[ n=1 \text{ RWM} \]

\[ n>1 \text{ RWM} \]

FIRE-AT1

FIRE-AT0

FIRE

FIRE*

ARIES-RS

ARIES-I

neoclassical tearing

5.3 MA, 8.5T, 35s, 150 MW

6.5 MA, 10T, 18s, 150 MW

7.7 MA, 10T, 18 s, 150 MW

150 MW
TSC Simulation of a “Fusion Dominated” Plasma

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

Q = 7.8, f_\alpha = 61% 

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

---

*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>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, 20s @ Pdt ~ 150 MW)</td>
</tr>
<tr>
<td>Pulse repetition time</td>
<td>~3hr @ full field and full pulse length</td>
</tr>
<tr>
<td>ICRF heating power, maximum</td>
<td>20 MW, 100MHz for 2$\Omega_T$, 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$2.5km/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**
  
  \[ R = 2.14 \text{ m}, \ a = 0.595 \text{ m} \]
  
  \[ B = 10 \text{ T}, \ Ip = 7.7 \text{ MA}, \]
  
  20 s flat top, \( P_{fus} = 150 \text{ MW} \)

- **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**
  
  (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

ARIES-RS The “Goal”

B = 10 T
R = 2.14 m
Pfusion = ~ 150 MW
Volume = 27 m³

B = 8 T
R = 5.5 m
Pfusion = 2170 MW
Volume = 350 m³
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
### 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 (m$^3$)</td>
<td>11</td>
<td>27</td>
<td>108</td>
<td>390</td>
<td>350</td>
<td>828</td>
</tr>
<tr>
<td>Plasma Surface (m$^2$)</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 ($\text{B-2000}$)</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}
• 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.
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