Fusion is an Outstanding Physics Challenge and is Connected to Other Outstanding Challenges

December 1999

Ten Outstanding Physics Challenges

- Quantum gravity presents the ultimate challenge to theorists
- Explaining high-$T_c$ superconductors
- Unstable nuclei reveal the need for a complete theory of the nucleus
- Realizing the potential of fusion energy
- Climate prediction is heavy weather
- Turbulence nears a final answer
- Glass physics: still not transparent
- Solar magnetic field poses problems
- Complexity, catastrophe and physics
- Consciousness: the physicists view
Can we Solve the Mystery of Producing a Stationary Self-Sustained Fusion Fire??

Fusion: Power of the Cosmos Brought to Earth
A Brief History of FIRE

Where we are and Future Opportunities.

D. Meade
for the FIRE Team

Presented to
Office of Fusion Energy Science
Germantown, MD

February 13, 2001

http://fire.pppl.gov
Outline and Main Points

Rational, Mission, Requirements and Readiness for Burning Plasma Experiment

- a compelling case must be made that has broad support
- UFA Wkp, NSO-PAC and FESAC will help define mission and requirements

FIRE Scientific Basis and Performance Projections

- evolving in response to community input
- $Q \sim 10$ for $\geq 1.5$ skin times is goal (requires 7.7 MA @ 10T if ITER98H(y,2))
- add advanced tokamak (RS) capability

FIRE Engineering Basis

- Baseline wedged BeCu design meets new goals
- Looking for improvements - e.g., bucked and wedged TF

Plans
There are Three Principal Fusion Concepts

**Spherical Inertial**
- gravitational
- transient compression
- drive (laser-D/I, beam)
- radial profile
- time profile
- electrostatic

**Toroidal Magnetic**
- surface of helical B lines
- twist of helix
- twist profile
- plasma profile
- toroidal symmetry

**Reactivity Enhancement**
- muon catalysis
- polarized nuclei
- others?
## Magnetic Fusion Science

### Part I

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<th>Issues - Standard Model</th>
<th>Concept Developm't</th>
<th>Proof of Principle</th>
<th>Performance Extension</th>
<th>Fusion Conditions</th>
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<tr>
<td>Transport</td>
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<tr>
<td>Macro Stability</td>
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<td>Wave Particle</td>
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<tr>
<td>Boundary</td>
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</table>

**Improved Capability (more advanced)**

**Fusion Conditions** \( \{ (\rho^*, v^*, \beta), \text{edge, } P_{\alpha}/P_H \} \)

\( BR^{5/4} \)
### Magnetic Fusion Science

#### Part II

**Issues - Strongly Coupled in a Fusion (Burning) Plasma**

<table>
<thead>
<tr>
<th>Transport</th>
</tr>
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<tbody>
<tr>
<td>Macro Stability</td>
</tr>
<tr>
<td>Wave Particle</td>
</tr>
<tr>
<td>Edge</td>
</tr>
</tbody>
</table>

**Improved Capability (more advanced)**

**Fusion Conditions** \( \{ (\rho^*, v^*, \beta), \text{edge}, P_{\alpha}/P_H \} \)

**External-heating (control)**

**Self-heating (Self organization)**
Burning Plasma Physics is Widely Accepted as the Primary Objective for a Next Step in Fusion Science

- Grunder Panel (98) and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report (99) identified “integrated physics of a self-heated plasma” as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study (99) endorsed the burning plasma physics objective, and that the tokamak was technically ready for high-gain experiment. A burning plasma experiment should also have advanced tokamak capability.
- SEAB (99) noted that “There is general agreement that the next large machine should, at least, be one that allows the scientific exploration of burning plasmas” and if Japan and Europe do not proceed with ITER “the U. S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost.” ..... “In any event the preliminary planning for such as machine should proceed now so as to allow the prompt pursuit of this option.”
- NRC/FuSAC (00) - “The US scientific community needs to take the lead in articulating the goals of an achievable, cost-effective scientific burning plasma experiment, and to develop flexible strategies to achieve it, including international collaboration.”
NSO/FIRE Community Discussions

A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step in magnetic fusion.

- Presentations have been made and comments received from:
  - SOFT/France  Sep 98  IAEA/Japan  Oct 98  APS-DPP  Nov 98
  - FPA  Jan 99  APEX/UCLA  Feb 99  APS Cent  Mar 99
  - IGNITOR Wkshp  May 99  NRC/NAS  May 99  GAT  May 99
  - LLNL  May 99  VLT-PAC  Jun 99  MIT PSFC  Jul 99
  - Snowmass  Jul 99  PPPL/SFG  Aug 99  VLT-PAC  Jun 99
  - U. Maryland  Dec 99  DOE/OFES  Dec 99  VLT PAC  Dec 99
  - Dartmouth  Jan 00  Harvey Mudd  Jan 00  FESAC  Feb 00
  - ORNL  Feb 00  Northwest'n  Feb 00  U. Hawaii  Feb 00
  - Geo Tech  Mar 00  U. Georgia  Mar 00  PPPL  Mar 00
  - Naval Postgrad S  Mar 00  U. Wis  Mar 00/Apr00  EPS/Budapest  Jun 00
  - IPP/Garching  Jun 00  CEA/Cadarache  Jun 00  JET-EFDA  Jun 00
  - NSO-PAC  Jul 00  SOFT/Spain  Sep 00  IAEA/Italy  Oct 00
  - Int'l DB/Frascati  Oct 00  CRPP/Lausanne  Oct 00  ANS/TOFE  Oct 00
  - APS/DPP-ICPP  Oct 00  VLT-PAC  Dec 00  UFA BP Wkp  Dec 00
  - NSO-PAC2  Jan 01  MIT IAP  Jan 01  Columbia U.  Jan 01
  - DOE/OFES  Feb 01

- The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. Over 15,000 visitors from around the world have logged on to the FIRE web site since the site was initiated in July, 1999.
UFA Workshop on Burning Plasma Science

First Workshop - 90 participants - December 11-13, 2000 University of Texas

- Extension of Madison Forum, Snowmass discussions on burning plasmas.
- Focused on Sciences Issues for/by burning plasmas
- Five Science Issue Breakout groups were established:
  1. Energetic Alpha Particles Issues for a Burning Plasma
  2. Confinement, Transport and Self-heating in Burning Plasma
  3. Macrostability in a Burning Plasma
  4. Boundary Plasma Science
  5. Relationship of Burning Plasma Science to Other Fields
- Strong nonlinear coupling that will occur in a strongly burning plasma was an overall theme. Action Item - need to develop a more compelling case.
- Some sentiment that a BP might be boring, that is, extrapolation too small from existing parameters. Others, expressed concern that strongly burning plasmas in an AT configuration with high bootstrap would be uncontrollable. Several areas identified where tokamak BP would shed light on understanding science issues for other configurations.
Next Step Option PAC is Engaged and Active.

- **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 11-12, 2001 at Univ. Wisc, Madison, WI

- **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.
Common Themes Emerging from NSO-PAC, UFA Workshop and Community Discussions

Scientific Basis
an experiment with flexibility, affordable first step with capability for later upgrades.

- able to access fusion dominated \( (P_\alpha / P_{\text{heat}} \geq 50\%) \)
  - increased \( I_p \) from 6.44 MA to 7.7 MA
  - reduced aspect ratio to 3.6
  - increased size \( R = 2.0m \) to 2.14m

- plasma sustained at least 1 - 2 skin times

- address issues central to fusion science
  - developing AT scenario for FIRE

Technical Basis and Status
LN Cu coil tokamak can satisfy the scientific requirements. What is the optimum config.?

- Baseline Wedged (BeCu) design meets requirements, will start peer review critical systems.
- Beginning design of a Bucked and Wedged (Cu) Configuration.
- Internal hardware and PFCs are a common challenge for tokamaks and other MF configs.

Community Involvement
Must develop a more exciting and compelling case for a next step magnetic fusion exp't.

- Presently an outreach emphasis, must transition to greater community involvement.
- UFA workshops, Science Initiatives for NSO, etc are opportunities for progress.
**Steps from the Vision to FIRE**

**Vision** (the public inspiration)
- HEP, NASA

**Mission** (statement for broad physics community)

**Scientific Objectives** (workscope for the fusion/plasma community)

**Plasma Parameters** (needed to address objectives)

**Device Parameters** (needed to produce plasma parameters)

**Project Cost must be affordable (if not reduce the mission)**
Vision and Mission for a Major Next Step in Magnetic Fusion

FIRE Vision Statement (some suggestions)

- Lighting the Fusion Fire
- Lighting the Way to the Future
- Exploring, Explaining and Expanding the frontiers of plasma science

FIRE Mission Statement

“Attain, explore, understand and optimize alpha fusion-dominated plasmas to provide knowledge for the design of attractive MFE magnetic fusion systems.”
Fusion Science Objectives for a Major Next Step Magnetic Fusion 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.
Attractive MFE Reactor (e.g. ARIES Vision)

Existing Data Base
Emerging Advanced Toroidal Data Base

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

Burning Plasma Physics
Advanced Toroidal Physics

Physics Integration Experiment
Burning Plasma Physics and Advanced Toroidal Physics

Existing Devices
Existing Data Base, Emerging Advanced Toroidal Data Base

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

The “Old Paradigm” required three separate devices, the “New Paradigm” could utilize one facility operating in three modes or phases.
Requirements for a Next Step Burning Plasma Experiment

Note: these are the projections on to the 2-D planes.

$f_{ss}$ is the plasma current equilibration fraction
### Dimensionless Parameters Required for Fusion Plasma Physics Experiment

<table>
<thead>
<tr>
<th>Explore and Understand Fusion Plasmas</th>
<th>Core* Edge</th>
<th>Alpha</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy and Particle Transport</td>
<td>BR^{5/4}</td>
<td>P_{\alpha}/P_{\text{heat}}</td>
<td>\tau/\tau_{\alpha S}</td>
</tr>
<tr>
<td>Macroscopic Stability</td>
<td>&gt;0.5</td>
<td>&gt;0.5</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Wave Particle (alpha heating, fast alpha)</td>
<td>?</td>
<td>\beta_{\alpha} \sim \text{ARIES}</td>
<td>10</td>
</tr>
<tr>
<td>Plasma Boundary</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>10</td>
</tr>
<tr>
<td>Test Control and Optimization Techniques</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>3 to 5</td>
</tr>
<tr>
<td>Profile evolution impact on \tau_E, MHD</td>
<td>&gt;0.5</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Sustain Fusion-Dominated Plasmas</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>3 to 5</td>
</tr>
<tr>
<td>Exhaust of power, particles and ash</td>
<td>&gt;0.5</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
</tr>
<tr>
<td>JET/TFTR D-T Experiments</td>
<td>&gt;0.3</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
</tr>
<tr>
<td>ARIES-AT</td>
<td>1</td>
<td>0.9</td>
<td>&gt;10</td>
</tr>
<tr>
<td>FIRE Goals</td>
<td>0.6</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
</tr>
<tr>
<td>JET/TFTR D-T Experiments</td>
<td>0.3</td>
<td>0.04</td>
<td>~3</td>
</tr>
</tbody>
</table>

* Core parameters are normalized to ARIES-AT BR^{5/4}
Dimensionless Parameters for 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

- **Size - Number of Gyro-Radii**
  - a/ρ_i vs. n/n_GW
  - Lines for ITER-FEAT, FIRE*, JET-U

- **Normalized Collisionality**
  - ν* vs. n/n_GW
  - Lines for ITER-FEAT, FIRE*, JET-U

- **Thermal Beta**
  - β_therm % vs. n/n_GW
  - Points for ITER-FEAT, FIRE*, JET-U
  - Labels: 1.93, 1.7

- **Duration - Skin times**
  - τ_burn/τ_skin vs. n/n_GW
  - Lines for ITER-FEAT, FIRE*, JET-U
**Summary Points on Dimensionless Parameters**

- FIRE is a modest extrapolation in $\rho^*$ and $\nabla \beta_\alpha$, is this good or bad?
- Other FIRE and ITER-FEAT dimensionless parameters are quite close.
- JET-U (4T, 6 MA) parameters are substantially less, esp Q or $f_\alpha = P_\alpha / P_{\text{heat}}$. Large population of RF or NB ions will damp EPM/TAE modes.
Plans (Ideas) for Vision and Mission Development

• Look for guidance from the UFA Burning Plasma Science Workshop Series
  followup on action items
  more active involvement of the community

• Respond to FESAC Burning Plasma Review

• Continue outreach activity ~ 30 talks in last 18 months, 1/3 non-fusion audiences
  extend discussions and visits within the fusion community
  actively participate/discuss with broader physical sciences community
    Spring APS in Washington, DC, AAAS meetings, HEP Snowmass?
    Accelerator laboratories - physics and enabling technology
    High Field Magnet Community, NASA science and technology

• Extend web site - excellent response from all over the U.S. and world
Status of Laboratory Fusion Experiments

LAWSON PARAMETER, \( n_i \) (\( 10^{20} \text{m}^{-3} \text{s} \))

CENTRAL ION TEMPERATURE, \( T_i \) (0) (keV)

Legend
- Red: D-T
- Green: D-D
- Blue: Nova direct drive
- Pink: Nova indirect drive
- Black: Laser D-T

Higher Density Magnetic
Moderate Density Magnetic
Ignition
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
Fusion Ignition Research Experiment (FIRE)

Design Goals

- $R = 2.0 \text{ m}$, $a = 0.525 \text{ m}$
- $B = 10 \text{ T}$, $(12\text{T})^*$
- $W_{\text{mag}} = 3.8 \text{ GJ}$, $(5.5\text{T})^*$
- $I_p = 6.5 \text{ MA}$, $(7.7 \text{ MA})^*$
- $P_{\alpha} > P_{\text{aux}}$, $P_{\text{fusion}} < 200 \text{ MW}$
- Burn Time $\approx 18.5\text{s}$ $(\approx 12\text{s})^*$
- Tokamak Cost $\leq 0.3\text{B}$
- Base Project Cost $\leq 1\text{B}$

* Higher Field Mode

Cost goal drives one to the smallest size and constrained mission.

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.
### Basic Parameters and Features of FIRE Reference Baseline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R, major radius</strong></td>
<td>2.0 m</td>
</tr>
<tr>
<td><strong>a, minor radius</strong></td>
<td>0.525 m</td>
</tr>
<tr>
<td><strong>κ95, elongation at 95% flux surface</strong></td>
<td>~1.8</td>
</tr>
<tr>
<td><strong>δ95, triangularity at 95% flux surface</strong></td>
<td>~0.4</td>
</tr>
<tr>
<td><strong>q95, safety factor at 95% flux surface</strong></td>
<td>&gt;3</td>
</tr>
<tr>
<td><strong>Bt, toroidal magnetic field</strong></td>
<td>10 T with 16 coils, 0.34% ripple @ Outer MP</td>
</tr>
<tr>
<td><strong>Toroidal magnet energy</strong></td>
<td>3.7 GJ</td>
</tr>
<tr>
<td><strong>Ip, plasma current</strong></td>
<td>~6.5 MA (7.7 MA at 12 T)</td>
</tr>
<tr>
<td><strong>Magnetic field flat top, burn time</strong></td>
<td>26 s at 10 T in dd, 18.5 s @ Pdt ~ 200 MW</td>
</tr>
<tr>
<td><strong>Pulse repetition time</strong></td>
<td>~3 hr @ full field and full pulse length</td>
</tr>
<tr>
<td><strong>ICRF heating power, maximum</strong></td>
<td>30 MW, 100MHz for 2ΩT, 4 mid-plane ports</td>
</tr>
<tr>
<td><strong>Neutral beam heating</strong></td>
<td>None, may have diagnostic neutral beam</td>
</tr>
<tr>
<td><strong>Lower Hybrid Current Drive</strong></td>
<td>None in baseline, upgrade for AT phase</td>
</tr>
<tr>
<td><strong>Plasma fueling</strong></td>
<td>Pellet injection (≥2.5km/s vertical launch inside mag axis, possible guided slower speed pellets)</td>
</tr>
<tr>
<td><strong>First wall materials</strong></td>
<td>Be tiles, no carbon</td>
</tr>
<tr>
<td><strong>First wall cooling</strong></td>
<td>Conduction cooled to water cooled Cu plates</td>
</tr>
<tr>
<td><strong>Divertor configuration</strong></td>
<td>Double null, fixed X point, detached mode</td>
</tr>
<tr>
<td><strong>Divertor plate</strong></td>
<td>W rods on Cu backing plate (ITER R&amp;D)</td>
</tr>
<tr>
<td><strong>Divertor plate cooling</strong></td>
<td>Inner plate-conduction, outer plate/baffle- water</td>
</tr>
<tr>
<td><strong>Fusion Power/ Fusion Power Density</strong></td>
<td>200 MW, ~10 MW m-3 in plasma</td>
</tr>
<tr>
<td><strong>Neutron wall loading</strong></td>
<td>~3 MW m-2</td>
</tr>
<tr>
<td><strong>Lifetime Fusion Production</strong></td>
<td>5 TJ (BPX had 6.5 TJ)</td>
</tr>
<tr>
<td><strong>Total pulses at full field/power</strong></td>
<td>3,000 (same as BPX), 30,000 at 2/3 Bt and Ip</td>
</tr>
<tr>
<td><strong>Tritium site inventory</strong></td>
<td>Goal &lt; 30 g, Category 3, Low Hazard Nuclear Facility</td>
</tr>
</tbody>
</table>

**Higher Field Mode B = 12T and Ip = 7.7MA with a 12 second flat top has been identified. Also enhanced performance option B = 10T, Ip = 7.7 MA with 20 s burn with R = 2.14m**
FIRE would have Access for Diagnostics and Heating

(and Advanced Tokamak Stabilization Systems)

16 mid-plane ports  1.3m x 0.65m
32 divertor ports  0.5m x 0.2m (16 for cryopumps/cooling water
24 vertical ports  0.13m diam
FIRE Status

Physics - NSO PAC review with Action Plan to follow up on Recommendations
  • Mission endorsed (recommend even more excitement)
  • Evaluate FIRE performance on the basis of recent scalings e.g., ITER98(y,2) and recent results with enhanced regimes e.g., pellet fueling
  • Enhanced performance design point has been developed with \( I_p = 7.7 \text{ MA} \) to increase confidence of high gain while maintaining pulse length (\( \sim 1.5 \tau_{cr} \))
  • Potential for advanced tokamak modes is being developed

Engineering
  • Pre-Conceptual Design Activity has addressed all subsystems. Engineering Report 2000 completed, see [http://fire.pppl.gov](http://fire.pppl.gov). CD is available on request
  • Baseline design of 10 T/20 s flat top and 12 T/12 s flat top exceeds original design goals of 10 T/10 s flat top.
  • Actively cooled W outer divertor and baffle with conduction cooled inner W divertor, and Be first wall on Cu substrate satisfy cooling requirements.
  • Cost Estimate of Baseline design gives $1.2B(FY-99$) for Green Field site with good possibility of < $1B(FY-99$) at an existing site.
  • FIRE* (7.7 MA, 10 T, 20 s flat top, \( R = 2.14 \text{ m}, a = 0.595 \text{ m}, A = 4 \)) is preferred option for increasing plasma performance, and is within original engineering margins for coils and structure. Divertor and first wall similar to baseline.
FIRE has Advanced Tokamak Capability and Flexibility

**AT Features**

- DN pumped divertor
- strong shaping
- very low ripple
- 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.*
Extend FIRE Confinement Projection Activities: NSO-PAC

Design Guidelines
• Similar to ITER-FEAT
  - Campbell APS paper on FIRE, ITER-FEAT presentation to TAC 7/00
  - Uckan, Wesley ANS paper
  - Meade, IAEA, ANS papers

Confinement Database Meeting (DB4)
• Library of reproducible shots (eg Barabaschi EPS paper)

FIRE Specific Assumptions
• JET H-mode data base of FIRE-like shots (55)
  \( \kappa \geq 1.7, \beta_N > 1.7, 2.7 < q_{95} < 3.5, Z_{\text{eff}} < 2, 0.3 < n/n_{GW} < 0.8 \)

  • \( <H(y,2)> = 1.1, \ <n(0)/<n>_v> = 1.2 \)

  • density peaking \( \approx 1.2 \) consistent with 1-D modeling (e.g., Houlberg-ANS)

  • Impurity assumption needs more analysis. Not taking credit for reduction at high density, but must make sure hi-Z ions do not get into core plasma.

Starting interactions with theory-based modeling groups.
Guidelines for Estimating FIRE 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 tokamak data base (IPBDB4)

\[ n_{20} \leq 0.80 n_{GW} = 0.80 \frac{I_p}{\pi a^2} \]

Beta Limit - theory and tokamak data base

\[ \beta \leq \beta_N I_p / aB, \quad \beta_N < 2.5 \text{ conventional, } \beta_N \sim 3 - 4 \text{ advanced} \]

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 \( \tau_{He} = 5 \tau_E, \quad \text{impurities} = 3\% \text{ Be} \)

Most analyses published for FIRE have 3\% Be while ITER at 1/6 the operating density has 2\% Be. Some very recent cases for FIRE assume nBe \sim 1/n relative to ITER or 0.4\% Be.
FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters

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

Similarity Parameter

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

Kadomtsev, 1975

\[ B \tau_{Eth} \sim \rho^{*-2.88} \beta^{-0.69} \nu^*^{-0.08} \]
FIRE can Access Most of the H-Mode Database

FIRE
n/n_{GW} ≥ 0.30

ITER-FEAT
n/n_{GW} ≥ 0.85

H(y,2)

n/n_{GW}

ITER-FEAT TAC Meeting
June 2000
JET H-Mode Data Selected for FIRE-like Parameters

\[ <H(y,2)> = 1.1 \]
\[ <n(0)<n> > = 1.2 \]

This approach discussed at IAEA(Sorrento) and at the International Confinement Database meeting (Frascati).
Confinement Enhancement Required to Access Various Q-values Compared with JET H-Mode Data

\[ H(y,2) \]

- JET Data
- \( \beta_N > 1.7, \)
- \( 2.7 < q_{95} < 3.5, \)
- \( \kappa > 1.7, \)
- \( Z_{\text{eff}} < 2.0 \)

Base 12T, 7.7 MA
FIRE* 10T, 7.7 MA
Base 10T, 6.4 MA
Percentage of JET FIRE-like Data Points that Project to a Specific Alpha Heating Fraction (Q)

ITER98(y,2)
\( n(0)/\langle n \rangle = 1.2 \)

Base 10T
FIRE*
Base 12T

\( Q = 5 \)
0 10 20 30 40 50 60 70 80 90 100

0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Alpha Heating Fraction
Projections of FIRE Compared to Envisioned Reactors

JET H-Mode Data Base

FIRST “ITER” Reactor

FIRE*

Projections of FIRE Compared to Envisioned Reactors

* JET H-Mode Data for
  $\beta_N > 1.7$, $2.7 < q_{95} < 3.5$
  $\kappa > 1.7$, $n/n_{GW} = 0.5 - 0.8$, and $Z_{eff} < 2$ have

$$<H_{98}(y,2)> = 1.1$$
$$<n(0)/<n>_V> = 1.2$$
Projections of FIRE Performance as Confinement is Enhanced Toward that Required for Attractive Reactors

\[ \text{Alpha Heating Fraction} = \frac{P_{\alpha}}{P_{\alpha} + P_{\text{ext}}} \]

Alpha heating fraction, the science goal, is less sensitive to confinement uncertainty.
Sensitivity Scans on FIRE*

\[(A = 3.60, \kappa_95 = 1.77, \delta_95 = 0.4, \text{ITER98(y,2), } H = 1.027, \text{ } n/nGW = 0.7, n\text{Be} = 0.4\%\]

Note: kappa area would make \( H = 1.01 \)
1 1/2-D Simulation of Burn Control in FIRE

- ITER98(y, 2) scaling with $H(y,2) = 1.1$, $n(0)/<n> = 1.25$ and $n/n_{GW} = 0.59$

- Pulse Duration $\approx 30 \tau_E$, $6 \tau_{He}$ and $\sim 1.5 \tau_{skin}$

http://fire.pppl.gov
FIRE could Access High-Gain Advanced Tokamak Regimes for Long Durations

- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- FIRE, with strong plasma shaping, flexible double null poloidal divertor, low TF ripple, dual inside launch pellet injectors, and space reserved for the addition of current drive (LHCD) and/or a smart conducting wall, has the capabilities needed to investigate advanced tokamak regimes in a high gain burning plasma.

- The LN inertially cooled TF coil has a pulse length capability ~250 s at 4T for DD plasmas. This long pulse - AT capability rivals that of any existing divertor tokamak or any under construction. The coils are not the limit.

- Recent AT regimes on DIII-D (Shot 98977) sustained for ~ 16 $\tau_E$ serve as demonstration discharges for initial AT experiments on FIRE. Need to develop self-consistent scenarios with profile control on FIRE with durations ~ 3 $\tau_{skin}$. 
FIRE could Access “Long Pulse” Advanced Tokamak Mode Studies 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 combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range from steady-state non-burning advanced-tokamak modes to “quasi-equilibrium” burning plasmas in advanced tokamak modes.
FIRE can Access MHD Regimes of Interest from Today's Data Base to those Envisioned for ARIES-RS

FIRE-RS
- $q^* = 2$
- $4.5MA, 82\% Ibs$
- $6.75T, 60s, 150 MW$

FIRE-RS
- $q^* = 3$
- $q(0) = 2.9,$
- $q_{\text{min}} = 2.6,$
- $q_{95} = 4.6$

FIRE-RS
- $q^* = 4$
- $\beta_N = 5$

ARIES-RS
- $\beta_N = 3$

ARIES-I
- $\beta_N = 2$

ITER
- $\beta_N = 4$

SSTR
- $220 MW$
- $5.65MA, 60\% Ibs$
- $9T, 25s, 150 MW$
- $4.82MA, 70\% Ibs$
- $7.5T, \sim 37s, 150 MW$
- $5.2MA, 60\% Ibs$
- $8.25T, 30s, 150 MW$

FIRE
- $4.5MA, 82\% Ibs$
- $6.75T, 60s, 150 MW$
- $7.7MA$
- $12T, 12s$
- $250 MW$

FIRE
- $4.82MA, 70\% Ibs$
- $7.5T, \sim 37s, 150 MW$
- $5.2MA, 60\% Ibs$
- $8.25T, 30s, 150 MW$
- $5.65MA, 60\% Ibs$
- $9T, 25s, 150 MW$
- $6.5MA$
- $10T, 18s$
- $220 MW$

ARIES-RS
- $6.5MA$
- $10T, 18s$
- $220 MW$

ARIES-I
- $5.65MA, 60\% Ibs$
- $9T, 25s, 150 MW$
- $4.82MA, 70\% Ibs$
- $7.5T, \sim 37s, 150 MW$
- $5.2MA, 60\% Ibs$
- $8.25T, 30s, 150 MW$
- $6.5MA$
- $10T, 18s$
- $220 MW$

FIRE
- $4.5MA, 82\% Ibs$
- $6.75T, 60s, 150 MW$
- $7.7MA$
- $12T, 12s$
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FIRE-RS
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FIRE-RS
- $q^* = 2$
- $4.5MA, 82\% Ibs$
- $6.75T, 60s, 150 MW$
- $7.7MA$
- $12T, 12s$
- $250 MW$
Potential for Resistive Wall Mode Stabilization System

view of horizontal port front looking from plasma side

Concept under development by Columbia Univ. J. Bialek, G. Navratil, C.Kessel(PPPL) et al
### Cost Drivers

<table>
<thead>
<tr>
<th></th>
<th>ARIES-ST</th>
<th>ITER-FEAT</th>
<th>ARIES-RS</th>
<th>JET</th>
<th>FIRE*</th>
<th>IGNITOR</th>
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<tbody>
<tr>
<td><strong>Plasma Volume (m³)</strong></td>
<td>810</td>
<td>828</td>
<td>350</td>
<td>95</td>
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<td>11</td>
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<td><strong>Plasma Surface (m²)</strong></td>
<td>580</td>
<td>678</td>
<td>440</td>
<td>150</td>
<td>67</td>
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<td><strong>Plasma Current (MA)</strong></td>
<td>28</td>
<td>15</td>
<td>11</td>
<td>4</td>
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<tr>
<td><strong>Magnet Energy (GJ)</strong></td>
<td>29</td>
<td>50</td>
<td>85</td>
<td>2</td>
<td>7</td>
<td>5</td>
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<tr>
<td><strong>Fusion Power (MW)</strong></td>
<td>3000</td>
<td>400</td>
<td>2200</td>
<td>16</td>
<td>150</td>
<td>100</td>
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<tr>
<td><strong>Burn Time (s), inductive</strong></td>
<td>steady</td>
<td>steady*</td>
<td>300</td>
<td>1</td>
<td>20</td>
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* assumes non-inductive current drive
# FIRE Power Requirements for BeCu or CuTF Coils

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<thead>
<tr>
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<th>10T (20s flattop)</th>
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<th>12T (12s flattop)</th>
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<tr>
<td><strong>BeCu</strong></td>
<td>Peak Power (MW)</td>
<td>Peak Energy (GJ)</td>
<td>Peak Power (MW)</td>
<td>Peak Energy (GJ)</td>
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<tr>
<td>TF</td>
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<td>11.5</td>
<td>815</td>
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<td>PF</td>
<td>250</td>
<td>2.2</td>
<td>360</td>
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<tr>
<td>RF</td>
<td>60</td>
<td>1</td>
<td>60</td>
<td>0.6</td>
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<tr>
<td><strong>Σ</strong></td>
<td>800</td>
<td>14.7</td>
<td>1235</td>
<td>15.8</td>
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<tr>
<td>Grid</td>
<td>550 (TF&amp;RF)</td>
<td>12.5</td>
<td>600 (TFbase)</td>
<td>10.9</td>
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<tr>
<td>MG</td>
<td>250 (PF)</td>
<td>2.2</td>
<td>635 (TFsupp&amp;PF&amp;RF)</td>
<td>4.9</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>10T (45s flattop)</th>
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<th>12T (25s flattop)</th>
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<tbody>
<tr>
<td><strong>Cu</strong></td>
<td>Peak Power (MW)</td>
<td>Peak Energy (GJ)</td>
<td>Peak Power (MW)</td>
<td>Peak Energy (GJ)</td>
</tr>
<tr>
<td>TF</td>
<td>267</td>
<td>12.6</td>
<td>345</td>
<td>13.2</td>
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<tr>
<td>PF</td>
<td>250</td>
<td>5</td>
<td>360</td>
<td>4.6</td>
</tr>
<tr>
<td>RF</td>
<td>60</td>
<td>2.3</td>
<td>60</td>
<td>1.3</td>
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<tr>
<td><strong>Σ</strong></td>
<td>577</td>
<td>19.9</td>
<td>765</td>
<td>19.1</td>
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<tr>
<td>Grid</td>
<td>577 (All Systems)</td>
<td>19.9</td>
<td>404 (TF&amp;RF)</td>
<td>14.5</td>
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<tr>
<td>MG</td>
<td>0</td>
<td>0</td>
<td>360 (PF)</td>
<td>4.6</td>
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</tbody>
</table>

Wedged TF coil design requires BeCu (68% IACS) for the TF center leg.

Bucked and Wedged design could use Cu (100% IACS) for the TF coil.
# Preliminary FIRE Cost Estimate (FY99 US$M)

<table>
<thead>
<tr>
<th>Category</th>
<th>Estimated Cost</th>
<th>Contingency</th>
<th>Total with Contingency</th>
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<tbody>
<tr>
<td>1.0 Tokamak Core</td>
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<tr>
<td>1.1 Plasma Facing Components</td>
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<td>1.2 Vacuum Vessel/In-Vessel Structures</td>
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<tr>
<td>1.3 TF Magnets /Structure</td>
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</tr>
<tr>
<td>1.4 PF Magnets/Structure</td>
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<td></td>
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<tr>
<td>1.5 Cryostat</td>
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<td>1.6 Support Structure</td>
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<td>1.7 Cost Estimate</td>
<td>252.2</td>
<td>75.2</td>
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<td>2.0 Auxiliary Systems</td>
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<tr>
<td>2.1 Gas and Pellet Injection</td>
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<td>2.2 Vacuum Pumping System</td>
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<td>2.3 Fuel Recovery/Processing</td>
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<td>2.4 ICRF Heating</td>
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<td>2.8 Cost Estimate</td>
<td>134.6</td>
<td>39.3</td>
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<td>3.0 Diagnostics (Startup)</td>
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<td>4.0 Power Systems</td>
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<td>5.0 Instrumentation and Controls</td>
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<td>6.0 Site and Facilities</td>
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<td>7.0 Machine Assembly and Remote Maintenance</td>
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<td>8.0 Project Support and Oversight</td>
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<tr>
<td>9.0 Preparation for Operations/Spares</td>
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<tr>
<td><strong>Preconceptual Cost Estimate (FY99 US$M)</strong></td>
<td><strong>960.9</strong></td>
<td><strong>236.9</strong></td>
<td><strong>1193.5</strong></td>
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</tbody>
</table>

Assumes a Green Field Site with **No** site credits or significant equipment reuse.

This estimate is work in progress and will be reviewed in the winter 2000.

October 13, 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 information “exists now” to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.
Timetable for a Major Next Step in MFE

<table>
<thead>
<tr>
<th>FY</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
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<tbody>
<tr>
<td>EU Airaghi Report</td>
<td>ITER-EDA Extension Complete</td>
<td>JA Decision ITER/JT-60 SC</td>
<td>FuSAC Report</td>
<td>EU Response to Airaghi Report</td>
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</tbody>
</table>

**NSO/FIRE Activities**

- **Feasibility Study**
  - Establish Mission and Provisional Parameters
  - Initial Report

- **Preconceptual Design**
  - Mid-Term Report
  - Preconceptual Design Report

- **Resolve Technical Issues**
  - Divertor and PFCs, Disruptions
  - Vac Vessel Nuclear Heating, Remote Handling

- **Incorporate AT Capability**
  - Physics Scenarios: $\beta_N$, $f_{bs}$, wall stabilization
  - ripple, pulse length, current drive

- **Physics R&D**

- **Enabling Technology R&D**

**Snowmass on Burning Plasmas**

**CD-0, Approve Mission Need and Initiate Preproject planning activities.**
Some Initiatives Driven by a Next Step Experiment

• Transport and Turbulence in Burning Plasmas (session at next TTF meeting?)
  Physics based modeling
    Multi-Mode at Lehigh - Bateman, Kritz et al: have initiated studies
    Gyro-fluid at GA - Kinsey, Waltz, PPPL- Hammett - just beginning
    Pedestal physics is crucial - plasma density control and high triang.
  Similarity analysis and projection
    DIII-D/C-Mod - extension of existing programs

• Macroscopic Stability
  Analysis/Evaluation of Base and AT (e.g., RS) - Jardin/Ramos/Kessel
  RWM Stabilization Initiative - Columbia Univ. et al

• Wave Particle
  TAE/EPM Initiative - Detailed issues identified at UFA Wkshp
  CD for AT and NTM stabilization -

• Edge Physics
  Density Profile Control initiative - pellet fueling and pumped divertor - ORNL

An Integrated/Coupled Simulation Model would be a powerful tool for design of a NSO, and could then be benchmarked using an NSO.
Major Conclusions of the FIRE Design Study

- Exploration, understanding and optimization of fusion-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.

- The tokamak is a cost-effective vehicle to investigate fusion-dominated plasma physics and its coupling to advanced toroidal physics for MFE. The tokamak is technically ready for a next step to explore fusion plasma physics.

- The FIRE compact high field tokamak can address the important fusion-dominated plasma issues, many of the long pulse advanced tokamak issues and begin the coupling of fusion-dominated plasmas with advanced toroidal physics in a $1B class facility.

- The FIRE design point has been chosen to be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

- A plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-2 with the goal of being ready to begin a Conceptual Design in 2003.

http://fire.pppl.gov
Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science