Roadmapping an MFE Strategy

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EPRI Fusion Energy Assessment

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• The U.S. MFE program can break out into a directed energy development program whenever desired
  – An accelerated roadmap can make ITER the “penultimate” step to fusion energy

• Requires two major changes to the MFE enterprise
  – An accelerated fusion nuclear science and engineering program
  – Management of fusion energy development as a directed project rather than open-ended science research program
ACCELERATE MFE VIA FUSION NUCLEAR S&T PROGRAM IN ITER TIMEFRAME
The issues that need addressing for fusion energy have been repeatedly identified

- ITER as one major element: the science of a high gain (Q~10) burning plasma
  - Reactor-scale plasma science: confinement; stability
  - Reactor-relevant technologies: SC magnets; Heating and Diagnostics; initial TBM tests, some PWI, etc.

- U.S. community studies have many times identified the additional elements needed to move to fusion energy, recently
  - 2003: FESAC Plan for Fusion Energy Development
  - 2007-2009: FESAC Priorities, Gaps & Opportunities + ReNew
  - 2010: Fusion Nuclear Science Program (FNSP) White Paper
  - 2010: Pilot Plant concept development

- Similar efforts, and results, pursued by international partners

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The sequence of a fusion energy program is well-known

- Acceleration of generic steps involves parallelization and increased risk management

Figure XS3. Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma, fusion chamber and power technologies form the foundation for research on the major facilities.
Rollback Logic and Risk Assessment to Identify Critical Paths & Issues

Rollback (right-to-left) analysis:
1. What are S&T requirements for Demo?
2. What are its prerequisites?
3. What major facilities and programs are required to satisfy the prerequisites?
4. What are the tradeoffs?

(courtesy G. H. Neilson)
The FESAC 2007 Study Identified Gaps and Potential Means of Filling Them

### How Initiatives Could Address Gaps

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<td>1</td>
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<tr>
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<td>3</td>
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<td>No Important Contribution</td>
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</table>

I-1. Predictive plasma modeling and validation initiative

I-2. ITER – AT extensions

I-3. Integrated advanced physics demonstration (DT)

I-4. Integrated PWI/PFC experiment (DD)

I-5. Disruption-free experiments

I-6. Engineering and materials science modeling and experimental validation initiative

I-7. Materials qualification facility

I-8. Component development and testing

I-9. Component qualification facility

(from FESAC “Priorities, Gaps, and Opportunities...” 2007)
FUSION NUCLEAR SCIENCE AND TECHNOLOGY: USING AND DEALING WITH FUSION REACTIONS

• Producing significant fusion power in true steady state

• Breeding the T fuel

• Producing high-grade process heat from fusion

• Making chambers and blankets that survive high plasma and neutron fluences

• Measuring plasma properties in a high neutron environment

• Demonstrating advanced plasma performance at DEMO-scale

• Making electricity from the process heat

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Roadmap Building Blocks Come in Two Types

Major Integration Facilities
- Nuclear (e.g., ITER, Demo, Fusion Nuclear Facility)
- Best for integrated testing, validation, and demonstration.

Supporting Research and Development Activities
- Develop physics scenarios and engineering & technology elements individually or in subsets.
- Less integrated, more modular, more flexible.
- Range of sizes from small to > $1B.
- Best for developing and down-selecting options for integration facilities.
Tools for the Necessary Fusion Nuclear Science & Technology Program

Integration, validation tests

FN S&T

Fusion Nuclear Facility

High Performance Plasma Research
- US Tokamaks
  - NSTX
  - DIII-D
  - EAST
- KSTAR Asian Tokamaks
- SST
- JT60-SA
- Steady-State Heating and Current Drive

Plasma Material Interface Research

Power Extraction and Fusion Fuel Production Research

Tritium Processing Research

Fusion Materials Research

Nuclear Science Computation

Measurement in Nuclear Environment

Multi-Scale Neutron Transport

Materials Damage and Evolution

Instrumentation

Smaller-scale, “out-of-pile” studies of separable effects
Options for the Fusion Nuclear Facility

**Program Mission:**
Fill the gaps in ITER and existing fusion programs to support a FOAK DEMO construction

**FNF Objectives:**
- 2-6 MW/m² neutron fluxes for long times
- Test/validate materials
  - (low activation, high strength, high temperature, radiation resistant)
- Tritium breeding; self-sufficiency
- Produce high-grade process heat

**Add:**
- Enable DEMO-class high-performance plasma research
- Generate net electricity
- Reactor maintenance schemes

FNF choices lie on continuum between present program and DEMO

Present

DEMO step (2) size

FNF step (1) size

DEMO

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Any Intermediate Fusion Nuclear Facility will evolve in stages; e.g., FNF-ST

- **I-DD**: 1xJET, verify plasma operation, PMI/PFC, neutronics, shielding, safety, RH system
- **II-DT**: 1xJET, verify FNS research capability: PMI/PFC, tritium cycle, power extraction
- **III-DT**: 2xJET, full FNS research, basis for CTF
- **IV-DT**: 3xJET, “stretch” FNS & CTF research

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**Table: Stage-Fuel Parameters**

<table>
<thead>
<tr>
<th>Stage</th>
<th>I-DD</th>
<th>II-DT</th>
<th>III-DT</th>
<th>IV-DT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current, I_p (MA)</td>
<td>4.2</td>
<td>4.2</td>
<td>6.7</td>
<td>8.4</td>
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<tr>
<td>Plasma pressure (MPa)</td>
<td>0.16</td>
<td>0.16</td>
<td>0.43</td>
<td>0.70</td>
</tr>
<tr>
<td>W_t (MW/m^2)</td>
<td>0.005</td>
<td>0.25</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Fusion gain Q</td>
<td>0.01</td>
<td>0.86</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>0.2</td>
<td>19</td>
<td>76</td>
<td>152</td>
</tr>
<tr>
<td>Tritium burn rate (g/yr)</td>
<td>0</td>
<td>≤105</td>
<td>≤420</td>
<td>≤840</td>
</tr>
<tr>
<td>Field, B_t (T)</td>
<td>2.7</td>
<td>2.7</td>
<td>2.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Safety factor, q_cyl</td>
<td>6.0</td>
<td>6.0</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Toroidal beta, (\beta_T) (%)</td>
<td>4.4</td>
<td>4.4</td>
<td>10.1</td>
<td>10.8</td>
</tr>
<tr>
<td>Normal beta, (\beta_N)</td>
<td>2.1</td>
<td>2.1</td>
<td>3.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Avg density, (n_e) (10^{20}/m^3)</td>
<td>0.54</td>
<td>0.54</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Avg ion T_i (keV)</td>
<td>7.7</td>
<td>7.6</td>
<td>10.2</td>
<td>11.8</td>
</tr>
<tr>
<td>Avg electron T_e (keV)</td>
<td>4.2</td>
<td>4.3</td>
<td>5.7</td>
<td>7.2</td>
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<tr>
<td>BS current fraction</td>
<td>0.45</td>
<td>0.47</td>
<td>0.50</td>
<td>0.53</td>
</tr>
<tr>
<td>NBI H&amp;CD power (MW)</td>
<td>26</td>
<td>22</td>
<td>44</td>
<td>61</td>
</tr>
<tr>
<td>NBI energy to core (kV)</td>
<td>120</td>
<td>120</td>
<td>235</td>
<td>330</td>
</tr>
</tbody>
</table>

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- \(R_0 = 1.3\text{m}, A = 1.7\)
- \(H_N \leq 1.25, \beta/\beta_N \leq 0.75\)
- \(q_{cyl} \geq 4\)
- \(J_{TF-avg} \leq 4\text{kA/cm}^2\)
- Mid-plane test area \(\geq 10\text{m}^2\)
- Outboard T breeder \(\sim 50\text{m}^2\)

(courtesy M. Peng)
Pilot Plant is Within a Factor ~2 of Demo in Key Metrics to Minimize Risks in Last Step

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>Pilot Plant</th>
<th>Demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma duration (s)</td>
<td>500-3000</td>
<td>10^6-10^7</td>
<td>3x10^7</td>
</tr>
<tr>
<td>Engineering gain</td>
<td></td>
<td>1 - 3</td>
<td>4-6</td>
</tr>
<tr>
<td>Tritium sustainability (TBR)</td>
<td>none</td>
<td>1.0+</td>
<td>1.1</td>
</tr>
<tr>
<td>Avg. neutron wall load ⟨NWL⟩ (MW/m^2)</td>
<td>0.5</td>
<td>1-2</td>
<td>3-4</td>
</tr>
<tr>
<td>NWL at the test modules (MW/m^2)</td>
<td>0.7</td>
<td>1.5-3</td>
<td>4.5-6</td>
</tr>
<tr>
<td>Life of plant in years</td>
<td>20</td>
<td>20-30</td>
<td>30-40</td>
</tr>
<tr>
<td>Life of plant fluence (MW-y/m^2)</td>
<td>0.3</td>
<td>6-20</td>
<td>120-160</td>
</tr>
<tr>
<td>Life of blanket fluence (MW-y/m^2)</td>
<td>≥ 3</td>
<td>6 - 20</td>
<td></td>
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<tr>
<td>Blanket lifetime damage (dpa)</td>
<td>≥ 30</td>
<td>60 - 200</td>
<td></td>
</tr>
<tr>
<td>Total availability</td>
<td>2.5-5%</td>
<td>10-30%</td>
<td>50-85%</td>
</tr>
<tr>
<td>Plasma fusion gain, Q</td>
<td>5-10</td>
<td>5-7 (AT)</td>
<td>~30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17-42 (CS)</td>
<td></td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td>500</td>
<td>300-600</td>
<td>2,500</td>
</tr>
</tbody>
</table>

• Largest remaining gap is fusion gain Q (factor ~6), unless Pilot Plant is a stellarator.

(courtesy G. H. Neilson)
ACCELERATE MFE VIA FUSION NUCLEAR S&T PROGRAM IN ITER TIMEFRAME

Present → ITER timeframe 2020 - 2035 → Construct Decision 2025-2030
An Example Fast Track to Get to a Net Electric DEMO via Fusion Nuclear Facility

| ITER Key Schedule Elements | 16 | 17 | 18 | 19 | 2020 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 2030 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 2040 |
|----------------------------|----|----|----|----|------|----|----|----|----|----|----|----|----|----|------|----|----|----|----|----|----|----|----|----|----|----|
| Fusion Nuclear Science Facility (FNSF) and Program |   |    |    |    |      |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Commissioning Operation (H, D, DT pulsed) |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Show Significant Steady-State Fusion Power |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Helium Cooled Ceramic Breeder Blanket |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Show Fusion Can Produce Its Own Fuel |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Produce High Grade Process Heat From Fusion |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Show Fusion Can Produce Electricity |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Dual Coolant Lead Lithium Blanket |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Oxide Dispersion Strengthened Ferritic Steel Blanket |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Operate a Blanket With DEMO Relevant Irradiation Lifetimes |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Field Plasma Diagnostics Suitable for a Power Plant |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |

Fusion Materials Irradiation and Development Program:
| Materials and Full Components Irradiation in FNSF |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Accelerator Based Lifetime Irradiation Data |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Initial Data |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Triple Ion Beam Facility |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Data on ODS Ferritic Steel |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Fission Reactor Irradiations |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Data on ODS Ferritic Steel for DEMO |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Initiate Design |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Build |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Blanket Decision |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |
| Operation |   |    |    |    |      |    |    |    |    |    |    |    |    |    |    |      |    |    |    |    |    |    |    |    |    |    |    |

DEM0 design initiated by first plasma in ITER. DEM0 construction triggered by Q=10 in ITER, first phase accomplishments in FNSF, and materials data on ODS Ferritic Steel. FNSF enables choice between two most promising blanket types for DEM0.

(R. Stambaugh, FPA 2010 Annual Meeting)
East Asian Partners also considering fast tracks to DEMO

Korea

EU-JA “Fast-Track” on same time-scale
- Expedite further via eDEMO

China

EDemo /Pilot plant (20 years)
Electricity generation with reduced mission

Based on existing technologies:
Option 1: Pure Fusion
A PF-class with SC coils
A ST-type compact device
Option 2: Fusion – Fission hybrid
Fusion: Q=1-3, Pth=50-100MW
Fission: M=20-30, Pt = 0.3-1.5 GW
Or:
ITER-type machine with different blanket: Pt = 5 GW, Pe = 1.5 GW

(from J. Li, “The Future of Fusion” SOFE 2011)
Need to Projectize Fusion Energy Development

• Accelerated program will require analysis and capacity to decide on acceptable risk for each program element
  – An open-ended science research program will not take such decisions

• Run as directed project to move to DEMO
  – Existing fusion science program remains as performing support research

• Use modern project management for energy development
  – Risk management and mitigation, not risk avoidance
  – Expeditious directed decisions and risk assessment
    • Cost
    • Scope
    • Schedule
  – Likely needed for final selection of specific path(s) to follow

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A SIMPLE ROADMAP RESOLVES REMAINING ISSUES FOR A DECISION FOR DEMO

• Development path goes through ITER and a Fusion Nuclear Facility
  – Includes underlying fusion nuclear S&T support activities
  – Underlying fusion nuclear S&T program is needed now

• Roadmap and Prioritization Studies Underway
  – Evaluate risks/costs/readiness/schedule to facilitate prioritization
  – Complement world program and opportunities
  – Target down-select to specific FNF concept in 1-2 years

• The interests of the customer will determine the pace and prioritization of fusion energy choices
  – Especially true for near-term accelerated energy program, and for large next (FNF) steps
  – Need for magnetic fusion energy project

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