U.S. Fusion Road Map Study


Magnetic Fusion Program Leaders Road Map Study Group

FESAC Strategy Panel Public Meeting
Washingtonian Marriott
Gaithersburg, MD
July 9, 2014

http://fire.pppl.gov
Magnetic Fusion Program Leaders (MFPL) Road Map Study

**Goal:** Develop and assess three aggressive technically feasible paths for the US Fusion Program motivate a commitment to DEMO on the timescale of ITER $Q \approx 10$ experiments (nominally 2028) with DEMO by mid-century.

1) ITER directly to a Tokamak DEMO (possibly staged)

2) ITER plus Fusion Nuclear Science Facility leading to a Tokamak DEMO

3) ITER plus additional facilities leading to a QS - Stellarator DEMO

Each of these paths will include major aspects of a broad supporting research program.

**Working Group Members:**
Meade (Chair), Garofalo, Hill, Kessel, Lipschultz/Whyte, Morley, Navratil, Neilson, Rasmussen, Zinkle

We have made one pass through the Road Map, this work is in Progress.

**Status reports given at:** APS/DPP-2013, FPA-2013, 2nd IAEA DEMO Workshop, MIT-2014, Fusion Energy System Study - 2014, Columbia Univ - 2014
General Considerations

- Road Map driven by Goal and Associated Missions
  - Goal is a Fusion Power Plant (FPP)
  - Use recent ARIES Study to define general characteristics of DEMO/FPP
  - Mission structure is similar to EU Fusion Road Map and 2007 FESAC Report

- Strive for quantitative milestones and metrics as mileage markers
  - Quantitative dimensional and dimensionless Figures of Merit (FESAC 2007).
  - Technical Readiness Levels
    - EU Road Map used TRLs for materials and technology
    - NAS IFE Assessment 2013 used TRLs in IFE Road Map (p.162)

- Setup logic Framework for Mission milestones and Decision points

- Identify facilities needed to achieve mission milestones

- Detailed cost estimates are beyond scope our exercise, however must
  - identify compelling near term deliverables to bootstrap funding of later steps
### ARIES Studies Identified General Characteristics of Magnetic Fusion Power Plants

**Advanced Tokamak**

**Compact Stellarator**

<table>
<thead>
<tr>
<th></th>
<th>ARIES-ACT1</th>
<th>ARIES-ACT2</th>
<th>ARIES-CS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R(m)</strong></td>
<td>6.25</td>
<td>9.75</td>
<td>7.75</td>
</tr>
<tr>
<td><strong>B(T) / B_{max-coil}(T)</strong></td>
<td>6.0/10.6</td>
<td>8.75/14.4</td>
<td>5.7/15.1</td>
</tr>
<tr>
<td><strong>β_N / β_{tot} (%)</strong></td>
<td>5.6/6.5</td>
<td>2.6/1.7</td>
<td>-/6.4</td>
</tr>
<tr>
<td><strong>P_{Fusion} (MW)</strong></td>
<td>1813</td>
<td>2637</td>
<td>2440</td>
</tr>
<tr>
<td><strong>f_{bs} (%)</strong></td>
<td>91</td>
<td>77</td>
<td>~25</td>
</tr>
<tr>
<td><strong>&lt;Γ_n&gt; MWm^{-2}</strong></td>
<td>2.5</td>
<td>1.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

All steady-state at 1,000 MW_E

**ARIES Reference**
Major Mission Elements on the Path to an MFE Power Plant

Mission 1. Create Fusion Power Source

Mission 2. Tame the Plasma Wall Interface

Mission 3. Harness the Power of Fusion

Mission 4. Develop Materials for Fusion Energy

Mission 5. Establish the Economic Attractiveness, and Environmental Benefits of Fusion Energy

• Restatement of Greenwald Panel and ReNeW themes
• Each Mission has ~ five sub-missions
TRLs Express Increasing Levels of Integration and Relevance to Final Goal and can Identify R&D Gaps.

<table>
<thead>
<tr>
<th>TRL</th>
<th>Generic Description (defense acquisitions definitions)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and formulated.</td>
</tr>
<tr>
<td>2</td>
<td>Technology concepts and/or applications formulated.</td>
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<tr>
<td>3</td>
<td>Analytical and experimental demonstration of critical function and/or proof of concept.</td>
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<td>4</td>
<td>Component and/or bench-scale validation in a laboratory environment.</td>
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<tr>
<td>5</td>
<td>Component and/or breadboard validation in a relevant environment.</td>
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<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in relevant environment.</td>
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<td>7</td>
<td>System prototype demonstration in an operational environment.</td>
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<td>8</td>
<td>Actual system completed and qualified through test and demonstration.</td>
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<td>9</td>
<td>Actual system proven through successful mission operations.</td>
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</tbody>
</table>

Normally TRLs are applied to technology projects, here we are attempting to apply the concept to R&D activities – NAS IFE Report 2013 page 162, Table 4.3
ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 1: Create Fusion Power Source

<table>
<thead>
<tr>
<th>Technical Readiness Level</th>
<th>1</th>
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<tbody>
<tr>
<td>Attain Burning Plasma Performance</td>
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<td>Ba5/4, nTeTi, QDT</td>
<td>Now</td>
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<td>Control High Performance Burning Plasma</td>
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<tr>
<td>nT, nT, disruptiveity, ( \tau_{\text{controlled}} ), P_{\text{loss}}/P_{\text{heat}}</td>
<td>Now</td>
<td>Support Fac.</td>
<td>ITER</td>
<td>DEMO</td>
<td>FNSF</td>
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<td>Sustain Magnetic Configuration</td>
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<tr>
<td>( f_{\text{CDT}}, P_{\text{CDT}}/P_{\text{heat}} ), ... ( \tau_{\text{sustained}}/\tau_{\text{CR}} ), etc</td>
<td>AT</td>
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<td>ST</td>
<td>Now</td>
<td>Support Facilities (JT-60SA)</td>
<td>ITER</td>
<td>DEMO</td>
<td>FNSF</td>
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<td>Sustain Fusion Fuel Mix and Stable Burn</td>
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<td>( n_\text{D}(0)/n_\text{T}(0)/n_\text{i}(0)^2 ), Pop.Con stable, ( \tau ) long</td>
<td>Now</td>
<td>ITER</td>
<td>DEMO</td>
<td>FNSF</td>
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<tr>
<td>Attain High Performance Burning Plasma Compatible with Plasma Exhaust</td>
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<tr>
<td>( T_{\text{pre}}, n_{\text{ped}}, \text{fuel dilution}, P_{\text{core-rad}} )</td>
<td>Now</td>
<td>Support Fac.</td>
<td>ITER</td>
<td>DEMO</td>
<td>FNSF</td>
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</tbody>
</table>

Major Issues
- Can AT be sustained in DEMO relevant mode with low disruptiveivity?
- Does QSS confinement extend to BP regime?
- Can high performance be sustained in either with DEMO relevant PFCs?
- Can fuel mix be sustained in either?

More Work Needed here
- Compare with EU, NAS IFE Rpt, FESAC Materials Rpt
- Describe reqmts for each TRL with issues, milestones

Support Facilities
- Existing DD tokamaks (domestic and foreign)-ITPA List
- Upgrades to existing facilities
- New Facilities
Milestones can be Defined to Clarify TRLs

- **Attain high burning plasma performance**
  - TRL 4: Q~1 achieved in DT experiments in TFTR/JET & extended with DT in JET 2017 with a Be wall

- **Control high performance burning plasma**:
  - TRL 3: Q~1 DT experiments in TFTR/JET see self-heating
  - TRL 4: DIII-D ECH dominated ITER baseline experiments
    - JET DT experiments on TAE transport in Q~1 DT plasmas with Be walls

- **Sustain fusion fuel mix and stable burn**:
  - TRL 5: NBI Tritium fueling in TFTR/JET & cryo pellet injection technology

- **Sustain magnetic configuration-AT Configuration**:
  - TRL 4: Bootstrap current widely observed; non-inductive sustained plasmas observed on JT-60U & DIII-D using NBI-CD/LHCD/ECCD
  - TRL 5-6: DIII-D/K-STAR/JT-60SA observation of ≥80% bootstrap sustained plasma
    - EAST/K-STAR/WEST observation of RF & bootstrap sustained SS plasma

- **Sustain magnetic configuration-ST Configuration**:
  - TRL 3: Bootstrap current observed in NSTX; CHI demonstrated non-inductive current drive
  - TRL 4: NSTX-U demonstrate non-inductive start-up and sustainment extrapolable to FNSF-AT

- **Attain high burning plasma performance compatible with plasma exhaust**:
  - TRL 3: JET/DIII-D/ASDEX-U demonstration of detached divertor operation
  - TRL 4: JET/DIII-D/K-STAR demonstration of detached divertor in SS AT ITER like plasma
  - TRL 4: NSTX-U demonstration of advanced divertor operation in FNSF-ST like plasma
  - TRL 5: Test stand validation of long lifetime divertor PMI material
Mission 1: Create Fusion Power Source Gap

Fusion Plasma Sustainment Time (sec)

Add projected JT60-SA, EAST, KSTAR, W7-X,

FESAC IC Version, Modification of Kikuchi figure
## ITER + FNSF => Advanced Tokamak Demo Pathway

### Mission 2: Tame the Plasma Wall Interface

<table>
<thead>
<tr>
<th>Technical Readiness Level</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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</thead>
<tbody>
<tr>
<td>Remove Plasma Exhaust Heat and particles on Divertor and First Wall</td>
<td>Now</td>
<td>Support Fac.</td>
<td>ITER</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>$P_{\text{div}}/A_{\text{div}} &lt; 10,\text{MWm}^{-2}$, pulse length, $T_{\text{PFC}}$</td>
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<tr>
<td>Mitigate Transient Heat Loads (Elms/Disruptions) (integrated with plasma control issue)</td>
<td>Now</td>
<td>Support Fac.</td>
<td>ITER</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>$\text{MJm}^{-2}$, freq, freqxMJm$^{-2}$</td>
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<td>Disruption controlled</td>
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<td>Reduce Material Migration (erosion), dust mm per FPY</td>
<td>Now</td>
<td>Support Fac.</td>
<td>ITER</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>$Z_{\text{eff}}, P_{\text{rad-core}}, P_{\text{rad-edge}}$</td>
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<td>Control Plasma Contamination (He ash, impurities)</td>
<td>Now</td>
<td>ITER</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>$T_{\text{inventory}}(\text{KG-T}), \text{Material}, dpa, T_{\text{PFC}}$</td>
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<td>Minimize Tritium Retention</td>
<td>Now</td>
<td>ITER</td>
<td>higher?</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>$\text{dpa, FPY}$</td>
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<tr>
<td>Develop Neutron Resistant PFC/FW mat'l</td>
<td>Now</td>
<td>Support Facilities</td>
<td>ITER</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
<td></td>
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<tr>
<td>Similar to FESAC Materials and Technology Rpt TRL Chart Table 3.2.3 and 3.2.4</td>
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<tr>
<td>Major Issues</td>
<td>System analysis to establish plausibility of concept choice of material for FNSF - when?, How?, R&amp;D needed</td>
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<td>Test improved divertor configuration - where, when</td>
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<td>Identify critical PMI integration issues and focus facilities</td>
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<tr>
<td>Integrated test of PFC concept/material/tokamak-plasma</td>
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<td>Required pulse length, $H/D/T$, n-fluence,</td>
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<tr>
<td>Support Facilities</td>
<td>single effect - high power steady-state linear</td>
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<tr>
<td>toroidal - dedicate/upgrade existing facilities (JET-ILW, AUG, WEST, W7-X, MAST, EAST, KSTAR, JT-60SA, LHD, C-Mod, DIII-D, NSTX-U), or new specialized facility</td>
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</table>

Compare with EU assessment esp. DTT  
Road Map Annex 2, p.19
Mission 2: Tame the Plasma Material Interface Gap

- \( P_{\text{heat}}/S \leq 10 \text{ MWm}^{-2} \)
- \( P_{\text{div}}/A_{\text{div}} \leq 10 \text{ MWm}^{-2} \)

- \( P_{\text{heat}} = \text{plasma heating power} \)
- \( \text{effect of core radiation} \)
- \( \text{Update points- W7,EAST,West} \)
- \( \text{Label all points-achieved/planned} \)
- \( \text{role of linear machines} \)

Modification of FESAC-IC fig.
# ITER + FNSF => Advanced Tokamak Demo Pathway

## Mission 3: Harnessing the Power of Fusion


<table>
<thead>
<tr>
<th>Technical Readiness Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstrate Fusion Power Conversion</td>
<td>now</td>
<td>BT3F</td>
<td>ITER-TBM</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>Produce Required Tritium</td>
<td>now</td>
<td>Benchtop /Lab</td>
<td>BTEF</td>
<td>ITER-TBM</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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</tr>
<tr>
<td>Establish MTBF/MTTR of Blanket/FW Systems</td>
<td>now</td>
<td>Benchtop /Lab</td>
<td>BT3F / BTEF</td>
<td>ITER-TBM</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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</tr>
<tr>
<td>Tritium Fueling and Exhaust Processing</td>
<td>now</td>
<td>ITER, Other Tokamaks</td>
<td>FNSF</td>
<td>DEMO</td>
<td>DEMO</td>
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</tbody>
</table>

## Major Issues
- PbLi MHD Flow Control, Pressure Drop, Transport Phenomena
- PbLi Chemistry Control/Processing
- Helium-cooled FW and Structure Thermomechanics
- Fabrication and Reliability of Complex Structures Under Combined loads
- Component synergistic failure modes, rates and effects
- Mechanisms for n decrease in MTTR
- Plasma Exhaust Processing Time and Availability
- Simulating Fusion Environment in Non-Fusion Test Facilities

## Support Facilities
- Blanket Thermomechanics and Thermofluid Test Facility (BT3F)
- Bred Tritium Unit Cell and Extraction Test Facility (BTEF)
- Fuel Cycle Development Facility (FCDF)
- Remote Handling Development Facility (RHDF)
- ITER Test Blanket Module Experiments (ITER-TBM)

Summary of 1st IAEA DEMO Workshop Priority Activities

1) thermofluid-MHD behaviour of complex geometry, multi-channel blanket designs;
2) impact of neutron irradiation on properties and performance;
3) high duty-cycle plasma exhaust processing; and
4) remote handling and maintenance of blanket/FW components.

Facilities to address these issues are required for TBM, FNFs, and DEMO.
Blanket Facilities to Reduce Gaps for all Pathways

- **Fusion Power Conversion**
  - EU, CN, Blanket Test Facilities
  - Blanket Thermomechanics and Thermofluid Test Facility (BT3F)

- **Tritium Breeding**
  - EU, JA, CN
  - Bred Tritium Unit Cell and Extraction Test Facility (BTEF)

- **Reliability/Maintainability**
  - EU, CN, Remote Handling Facilities
  - Remote Handling Development Facility (RHDF)

- **Fuel and Exhaust Processing**
  - TSTA, TFTR, JET
  - Fuel Cycle Development Facility (FCDF)

- **Tritum Test-STAR, Fuel Cycle Development Facility (FCDF)**

- **EU DEMO**
  - EU DEMO:
  - EU, CN, Remote Handling Facilities
  - Remote Handling Development Facility (RHDF)

- **Facilities described in FESAC Materials & Technology Rpt 2012**

- **EU DEMO**
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**ITER + FNSF => Advanced Tokamak Demo Pathway**

**Mission 4: Materials for Fusion Power**

<table>
<thead>
<tr>
<th>Technical Readiness Level</th>
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<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td><strong>Conquer Neutron Degradation</strong></td>
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<tr>
<td>Science Based Design Criteria Them/Mech</td>
<td>Now</td>
<td>Non-Nucl Test</td>
<td>Stand Integ</td>
<td>FusNeutS</td>
<td>FNSF</td>
<td>ITER TBM</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>Explore Fabrication/Joining Trade offs</td>
<td>Now</td>
<td>Non-Nuc Test</td>
<td>FusNeutS</td>
<td>NNTS Integ</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>Resolve Compatibility and Corrosion Issues</td>
<td>Now</td>
<td>Non-Nuc TS</td>
<td>NNTS Integ</td>
<td>FNSF</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>Radiation Effects in Fusion Environment</td>
<td>Now</td>
<td>Ion/Fiss neut</td>
<td>FusNeutS</td>
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<tr>
<td>Mat'l Qualification in Fusion Environment</td>
<td>Now</td>
<td>Ion/Fiss neut</td>
<td>FusNeutS</td>
<td>FNSF</td>
<td>ITER TBM</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>Structural Stability</td>
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<tr>
<td>Mat'l Qualification in Fusion Environment</td>
<td>Now</td>
<td>Ion/Fiss neut</td>
<td>FusNeutS</td>
<td>FNSF</td>
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<tr>
<td>Mechanical Integrity</td>
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<tr>
<td>Fusion Environment Effects on Tritium</td>
<td>Now</td>
<td>NNTS</td>
<td>Ion/Fiss neut</td>
<td>ITER TBM</td>
<td>FNSF</td>
<td>FusNeutS</td>
<td>DEMO</td>
<td>Power Plant</td>
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<tr>
<td>Retention and Permeation</td>
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</tbody>
</table>

Based on Table 3.3.1 in FESAC Report: Opportunities for Fusion Materials Science Technology Research Now and in the ITER ERA, DOE/SC-0149

**Major Issues:**

**Support Facilities:**
- Non-nuclear Test Stands
- Non-nuclear Test Stands Partially Integrated
- Ion Beams and Fission Reactors
- Fusion Relevant Intense Neutron Source

14
Mission 4: Create Materials for Fusion Power Gap

Reduced Activation Ferritic Steel
9Cr RAFM

FNSF Goal

Modification of Zinkle fig.
Materials Facilities to Reduce Gaps for all Pathways

<table>
<thead>
<tr>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
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</thead>
<tbody>
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</tbody>
</table>

Fission Neutron Tests
- Spallation – SINQ, SNS, MTS
- Integrated Fission/Spallation Test

Neutron Materials Simulations
- EVEDA
- IFMIF

US Join EVEDA?
US Join IFMIF?

US Join ITER TBM?

EU DEMO
- CDA
- EDA
- Construction
- Operate

ITER TBM
FNSF
## Mission 5: Establish the Economic Attractiveness and Environmental Benefits of Fusion Energy

<table>
<thead>
<tr>
<th>Technical Readiness Level</th>
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<th>6</th>
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<tbody>
<tr>
<td>Establish Competitive Cost of Electricity</td>
<td>Now</td>
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<tr>
<td>Reduce Plant Capital Cost</td>
<td>Now (eg- reduce complexity, establish fusion relevant regulations, ....)</td>
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<tr>
<td>Increase Operating Availability</td>
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<tr>
<td>Demonstrate Safety and Environmental Benefits (separate Safety and Environmental?)</td>
<td>Now - TFTR/JET</td>
<td>ITER</td>
<td>DEMO</td>
<td>Power Plant</td>
<td>Support Pgm</td>
<td>FNSF</td>
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</tr>
<tr>
<td>Establish Safety Regulations for Fusion</td>
<td>Now</td>
<td>ITER</td>
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<tr>
<td>Facilitate and Exploit Innovation in Physics, Technology and Manufacturing</td>
<td>Now</td>
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<tr>
<td>(eg- higher B, more efficient current drive, reduce complexity, cheaper manufacturing, ....)</td>
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</tbody>
</table>

**Major Issues:**
- Total cost of fusion must be competitive
- Fusion program must remain vigilant to ensure that the safety and environmental advantages of fusion energy are realized.

**Support Facilities:**

**Other Important Activities that need to be considered**

### Mission 6: Establish Enabling Plasma Technology for Fusion Power Plant

- Should we have a full mission on this? It tends to get lost

- **Enabling Plasma Technologies**
  - Plasma Actuators
  - Development of Low Cost High Field Magnets
  - Development of an R&D to support Missions above

- **Plasma and Machine Diagnostics**
  - Plasma Control
  - Development of Diagnostics Compatible Fusion Environment

### Mission 7: Strengthening the Infrastructure supporting Fusion Research

- Educational
- Industrial
Mission / TRL Milestones can be used to Inform Decisions

<table>
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<tr>
<th>Year</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
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<th>2040</th>
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<tr>
<td>Create Fusion Power Source</td>
<td>ITER Basis</td>
<td>FNSF CDA</td>
<td>FNSF EDA</td>
<td>FNSF Const</td>
<td>DEMO CDA</td>
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<tr>
<td>TRL=4</td>
<td>5</td>
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<td>7.5?</td>
<td>9</td>
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<td>7.5?</td>
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<td>TRL=2</td>
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<td>7.5?</td>
<td>9</td>
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<tr>
<td>TRL=2</td>
<td>3</td>
<td>3</td>
<td>7.5?</td>
<td>9</td>
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<tr>
<td>Economic Attractiveness</td>
<td>ITER Initiate Construction</td>
<td>Define Mission</td>
<td>Initiate Operation</td>
<td>Gain~10 500 MW</td>
<td>DEMO Basis</td>
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<tr>
<td>Goal</td>
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Legend:
- ◇ Milestone
- ♦ Decision Point
- ★ Goal

ITER + FNSF => AT DEMO Pathway
FNSF(AT) Mission for ITER + FNSF => AT DEMO Pathway

Create Fusion Power Source
- Attain required AT BP Parameters ($H_{98}>1.1; \beta_N>2.8; 100\%\ NI$) for Steady-state
- Demonstrate AT BP plasma control and elimination of plasma transients
- Demonstrate fusion power stability and control of fusion power output
- Verify and Validate BP scenario Simulations for DEMO—what does this mean?

Tame Plasma Wall Interface
- Demonstrate Div Power Handling at DEMO Power Densities in Steady state
- Test Candidate Divertor Materials – Power & Particle, reactor relevant
- Verify and Validate for DEMO

Harness Fusion Power
- Demonstrate a closed fusion fuel cycle with TBR $\sim 1$ that projects to TBR$>1$ in DEMO
- Validate Candidate Fusion Blanket concept in a fusion environment ($\Gamma_n>1\ MW_n m^{-2}$)
- Extract high grade heat and produce some electricity for extended period of time
- Thermal mechanical tests of blanket modules in fusion enviroment, reliability data

Materials for Fusion Power
- Demonstrate components for $\sim 20 - 30$ dpa, He $\sim 100-300$ ppm
- Initial data of neutron effects on welds, etc (Engineering Feasibility-Finesse Stage II)
- Initial data component lifetime, reliability and replacement time
ITER + FNSF => AT DEMO Pathway
(Milestones to Initiate Construction of AT FNSF)

Create Fusion Power Source
• attain required AT Parameters ($H_{98}>1.1; \beta_N>2.8; 100\% \text{ NI}$) for $4 \tau_{cr}$
• demonstrate plasma control ($\leq 1$ unmitigated disruption per year)
• V&V AT Plasma Simulations for FNSF operating scenario,

Tame Plasma Wall Interface
• Demonstrate Exhaust Power Handling: $P/S =1-2 \text{ MWm}^{-2}$ with $P_{\text{div}}/A_{\text{div}} <10 \text{ MWm}^{-2}$, 1 week
• Qualify Candidate Divertor Materials – Temp, $T_{\text{retention}}$, erosion life, neutron effects
• V&V PMI Simulations for FNSF exhaust power handling integrated with core plasma

Harness Fusion Power
• Leading Candidate blanket concept identified and R&D taken to TRL~5
• Qualify Tritium Handling Plan
• Qualify Remote Maintenance Scheme

Materials for Fusion Power
• Identify blanket structural material and qualify up to 25 dpa
• Demonstrate viable materials and technology for continuous tritium extraction from fusion blankets

Establish Economic Attractiveness and Environmental Benefits of fusion
• Preliminary Safety Analysis approved
• Environmental Impact Statement approved

Need similar for ST FNSF
Is Pilot Plant FNSF a DEMO?
Milestones and Major Decisions in the QS-Stell Pathway

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
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<th>2020</th>
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<th>2040</th>
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<tr>
<td>Create Fusion Power Source</td>
<td>ITER Basis</td>
<td>QS Stellarator Basis</td>
<td>Stell-NS Basis</td>
<td>Confirm Basis</td>
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<td>Tame Plasma Wall Interface</td>
<td>ITER Basis</td>
<td>QS Stellarator Basis</td>
<td>Stell-NS Basis</td>
<td>Confirm Basis</td>
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<tr>
<td>Harness Fusion Power</td>
<td>Stell-NS Basis</td>
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<td>Stell-NS Basis</td>
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<td>Materials for Fusion Power</td>
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<td>W7-X</td>
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<td>QS Stell Exp</td>
<td>Initiate Construction</td>
<td>Decide NS Mission: BP or PP</td>
<td>Stell-NS</td>
<td>Initiate Construction</td>
<td>Initiate Operation</td>
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</tbody>
</table>

Legend
- **Diamonds:** Milestone
- **Stars:** Decision Point
- **Goal:**

Stell-NS = Stellarator Next Step
NS Mission Options:
- Burning Plasma (BP)
- Pilot Plant (PP)
Major Decisions for US Magnetic Fusion Program Road Map

<table>
<thead>
<tr>
<th>2000</th>
<th>2010</th>
<th>2020</th>
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<td>C-Mod, DIII-D, ASDEX-U, JET</td>
<td>NSTX-U, MAST-U</td>
<td>EAST, KSTAR</td>
<td>AT or ST for FNSF?</td>
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<td>Adv Tokamak Pathway</td>
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<td>WEST</td>
<td>AT OK for Demo Basis?</td>
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<td>JET</td>
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<td>PMI Facilities</td>
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<td>AT or ST FNSF</td>
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<td>Blanket Facilities</td>
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<tr>
<td>Stellarator Base Program</td>
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</table>
Concluding Remarks

• A 10 Year Strategic Plan should not be a simple roll forward, but must be based on, and driven by, a longer term vision i.e. a Road Map.

• The 10 Year Strategic Plan for fusion must identify several compelling deliverables that when accomplished will serve to increase support for fusion in the US. This will also help serve to focus the activities, and create a sense of urgency in the community.

• The Framework for a Fusion Road Map can help in identifying and assessing the critical issues, milestones and decision points. Congress/Administration need to be able to track progress through milestones and decision points.

• If one of the goals of the 10 Year Strategic Plan is for the U. S. to be among the world leaders in fusion – this will require a significant increase in funding, to levels comparable to EU funding ( $1.34B in 2014).