Safety considerations for Fusion Energy: From experimental facilities to Fusion Nuclear Science and beyond

1st IAEA TM on the Safety, Design and Technology of Fusion Power Plants

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Outline

- Overview of the US Fusion Program
- Current fusion safety activities in the US
- Safety challenges towards FNSF and beyond
- Conclusions
Goals of US DOE Fusion Energy Sciences Program

- Advance the **fundamental science** of magnetically confined plasmas to develop the **predictive capability** needed for a sustainable fusion energy source;

- Support the development of the scientific understanding required to design and deploy the **materials** needed to support a burning plasma environment;

- Pursue scientific opportunities and grand challenges in **high energy density plasma science** to better understand our universe, and to enhance national security and economic competitiveness;

- Increase the fundamental understanding of **basic plasma science**, including both burning plasma and low temperature plasma science and engineering, to enhance economic competitiveness and to create opportunities for a broader range of science-based applications.

Source: [http://science.energy.gov/fes/about/](http://science.energy.gov/fes/about/)

FES program mission is to expand the fundamental understanding of matter at very high temperatures and densities and build the scientific foundation needed to develop a fusion energy source
FES 10-year strategic plan was issued in 2015

- Strategic priorities over the next decade:
  - **Massively parallel computing** with the goal of validated whole fusion device modeling to enable a transformation in predictive power, required to minimize risk in future fusion energy development steps
  - **Materials science** as it relates to plasma and fusion sciences will provide scientific foundations for greatly improved plasma confinement and heat exhaust
  - Research and prediction of **transient events** that can be deleterious to toroidal fusion plasms confinement
  - Continued stewardship of **discovery plasma science**
  - **FES user facilities** will be kept works-leading through robust operations support and regular updates

Community engagement workshops are being organized to include input from the fusion community in each of these areas
## US fusion budget highlights

### Budget Categories

<table>
<thead>
<tr>
<th>Budget Categories</th>
<th>FY 2016 Request</th>
<th>FY 2016 Enacted</th>
<th>FY 2017 Request</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burning Plasma: Long Pulse</td>
<td>30,909</td>
<td>41,021</td>
<td>31,355</td>
</tr>
<tr>
<td>Burning Plasma: High Power</td>
<td>150,000</td>
<td>115,000</td>
<td>125,000</td>
</tr>
<tr>
<td>Discovery Plasma Science</td>
<td>47,332</td>
<td>67,224</td>
<td>46,216</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>420,000</strong></td>
<td><strong>438,000</strong></td>
<td><strong>398,178</strong></td>
</tr>
</tbody>
</table>

### Budget Element

<table>
<thead>
<tr>
<th>Budget Element</th>
<th>FY 2016 Request</th>
<th>FY 2016 Enacted</th>
<th>FY 2017 Request</th>
<th>FY 2017 budget highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Nuclear Science</td>
<td>9,835</td>
<td>11,252</td>
<td>10,000</td>
<td>Study plasma-facing materials, PMI, tritium retention, neutronics, and material corrosion issues. Scoping studies.</td>
</tr>
<tr>
<td>Materials Research</td>
<td>9,960</td>
<td>14,000</td>
<td>10,226</td>
<td>Study structural materials, helium damage, tungsten ductility.</td>
</tr>
</tbody>
</table>

**Ed Synakowski, FES budget presentation Feb 10 2016**

Within Long Pulse, the Fusion Nuclear Science sub-element includes safety, tritium research and scoping studies (FNSF)
Key US fusion safety and environment (S&E) capabilities

- **DOE Fusion Safety Standards** (Requirements and Guidelines, 1996) served to develop ITER safety basis and the safety objectives of US IFE and MFE fusion plant concepts

- **Neutronics and activation** analysis tools and studies (LLNL, UW, UCLA, ORNL)

- **Source term** characterization, tritium and dust research (INL, LLNL, LANL, SRNL)

- **Energy source** evaluations to understand chemical energy from oxidation of fusion structural and breeder materials (INL, LLNL)

- **Safety assessment methodologies** including off-normal event identification and incident/accident analysis methodologies, used to support ITER methodology for the Report of Preliminary Safety – RPrS (LLNL, INL)

- **Accident analysis tools**, such as INL’s MELCOR version modified for fusion applications, used by many domestic and international fusion programs including ITER (INL)

- Conceptual **power plan studies**, both IFE and MFE - next slide (UW, LLNL, INL, others)

With DOE FES decreased emphasis on fusion safety, design and technology of fusion power plants, international collaboration is more valued than ever
US IFE Studies

Source: University of Wisconsin-Madison Fusion Technology Institute
US MFE Studies

Source: University of Wisconsin-Madison Fusion Technology Institute
Despite significant progress, important S&E gaps remain

When assessing the S&E understanding to license a future US DEMO, a number of knowledge gaps have been identified (FESAC Priorities Panel Report):

1. **Computational tools needed to analyze the response of a fusion system to an off-normal event or accident**
2. **Understanding and quantifying the fusion source term will be required for licensing activities**
3. **Qualification of fusion components in the fusion DEMO environment will be required to validate the design and to demonstrate safety roles of key components**
4. **A waste management strategy for fusion must be developed**
5. **Experience with large scale remote handling will be important prior to DEMO**
Notional fusion development pathway from ITER to commercial plants

- **First strongly burning plasma**
  - **ITER**
    - Max damage: 3 dpa
    - Max plasma pulse: 500-3000s
    - TBR: ~0
    - $T_{\text{blanket}}, T_{\text{cool,exit}}$: 285C, 150C
    - Materials: 316SS, CuCrZr, Be, W, H$_2$O, SS304, SS430
  - **FNSF**
    - Max damage: 37-74 dpa
    - Max plasma pulse: 1-15 days
    - TBR: ~1.0
    - $T_{\text{blanket}}, T_{\text{cool,exit}}$: 550C, 650C
  - **DEMO**
    - Max damage: 100-150 dpa
    - Max plasma pulse: 15-365 days
    - TBR: 1.05+
    - $T_{\text{blanket}}, T_{\text{cool,exit}}$: 550C, 650C
  - **Power Plant**
    - Max damage: 150+ dpa
    - Max plasma pulse: 365+ days
    - TBR: 1.05
    - $T_{\text{blanket}}, T_{\text{cool,exit}}$: 550C, 650C
    - Materials: RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel

- **Demonstrate routine Power Plant Ops**
- **No technical gaps**
Gaps are being addressed under the scope of FNSF

- FNSF represents US vision of the intermediate step that would accommodate the complex integration of components and the extreme nuclear fusion environment, as well as the nuclear science and plasma physics.

- Within the FNSF study (initial scoping-phase will wrap-up in 2016), current safety research is focused on:
  - Safety code development
  - Accident identification and analysis
    - LOFA
    - LOVA
    - Combined LOCA (in-vessel, ex-vessel)
  - Material qualification strategies
  - Remote handling schemes

ARIES AT sector maintenance
Safety analysis methodology for FNSF

- Given the early design stage we are applying a deterministic approach characterized by conservative assumptions and bounding analysis
  - Identification of inventories at risk
  - Identification of release pathways
  - Accident identification and analysis
  - Design iteration
Example of MELCOR model development
Safety challenges - Source term

- Understanding of radioactive source term has advanced given experience feedback from existing machines and focused R&D activities for ITER, however significant uncertainties remain for both IFE and MFE next step devices

*Example of use of administrative limit for source term:*

- If disruptions are minimized in a future FNSF or MFE DEMO, dust source term is expected to decrease (and therefore tritium trapped in dust too). Dust is not expected to be an issue for IFE or stellarator machines
- To support FNSF/DEMO operations, tritium source term will increase (10’s of Kg)
- There are large uncertainties about solubility of tritium in breeder materials:  
  *In particular, need to understand tritium solubility in LiPb (next slide)*
Large variations exist in tritium solubility testing in LiPb

Factor of 100 difference in measured solubility could have a very large impact on inventories

- Chan and Veleckis work at ANL includes the widest parametric investigation (including title)
- Based on permeation through sealed iron capsules
- Most representative for T / LLE / Fe alloy systems
- Reiter results mostly at 400°C and with 90% background retention in Fe crucible
Recent research shows possible impact of neutron irradiation on LiPb tritium retention

- Enhanced tritium retention in neutron irradiated LiPb
- Analysis shows LiT was formed during irradiation
- Amount of LiT could increase after reaching solubility limit of tritium
- This could be a common issue for FNSF and other next step devices

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**Fig. 2.** TDS spectra of hydrogen isotopes released from Pb-16Li exposed to D₂ gas or irradiated with thermal neutron.

*Okuno et al. / Fusion Engineering and Design 88 (2013) 2328–2331*

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Coordinated R&D to understand tritium solubility in LiPb and other tritium breeding/extraction challenges would be very beneficial
Safety challenges: Source term mobilization
Disruptions and EM loads

- Plasma events in MFE tokamaks have potential for large electromagnetic loads on vessel, and runaway electrons
- This is not an issue for IFE nor stellarator devices
- Justification of EM loads based on modelling and extrapolation from existing tokamaks
- Even if major disruptions are not expected in FNSF, design should consider maximum loads and appropriate safety margin

Coordinated R&D needed to continue developing the tokamak plasma physics basis
Safety challenges: Source term mobilization
Explosion hazards

- Presence of hydrogen and dust in a fusion device poses H and dust explosion hazards
  - Minimization of inventories is key
- Hazard could be aggravated by chemical reactions with capability to produce H (e.g. beryllium-water or lithium-water)
- Large uncertainties exist on measurement of dust in hot surfaces (ITER has a focused R&D program)
- FNSF will consider elimination of water and/or inert atmosphere around hydrogen inventories, including vacuum vessel
- Additional work is needed to ensure this hazard is well controlled in next step devices as tritium inventories increase

Coordinated R&D with ITER and others would allow development of comprehensive hazards control strategies for fusion
Safety challenges - Routine releases

- US fission power plants release, on average, ~130 Ci (13 mg or ~0.2 μSv) of airborne HTO and ~260 Ci of liquid HTO each year (Source: Lee Cadwallader, ARIES 2011)

- Usual media overreaction:

  **Radioactive Rivers and Rain: Routine Releases of Tritiated Water From Nuclear Power Plants**

  EPA's Maximum Contaminant Level Goal for all radionuclides, including tritium, is zero.

- Public acceptance of tritium routine releases goes well below actual regulations (actual EPA limit for tritium in drinking water is 20,000 pCi/L)

- ITER operation shall provide demonstration of control of tritium routine releases to levels acceptable for regulation and the public

- Use of low-solubility fusion blanket materials such as PbLi can lead to permeation issues: control of releases will become more challenging as tritium inventories increase in FNSF and beyond

Understating tritium permeation mechanisms and routine releases from existing facilities and focused R&D is key for the future success of fusion
Safety challenges: Waste management

- Fusion can avoid generating high level waste
- However it will still produce large volumes of low level waste
- Recycling/reuse of fusion components is a key element of waste minimization strategy
- Development of low activation materials can avoid excessive dose and recycling costs, but may add up material fabrication cost and qualification requirements

L. El-Guebaly, *Fusion Science and Technology* 67 (1) 2015.
Activation of W in-vessel components at DEMO levels could challenge waste strategies

- IFE studies using pure W armor showed potential concerns for irradiation cycles at power plant level over ~2 years.

- ARIES studies also showed W alloys or W with impurities in divertor could reach WDR~1 (limit for shallow land burial) after ~3 yrs of operation.

- It could take 100s of years for some in-vessel components to classify as low level waste.

- Recycling could increase the activation, trade-offs need to be assessed.

**Figure 4.** Waste disposal rating of fully compacted divertor after 3.4 MWy/m² of irradiation.

- L. El-Guebaly, *Fusion Science and Technology* 60, 1 (2011)

Fusion waste strategies should consider not only minimization of activation but also volume minimization. Issues like tritiated waste disposal need to be considered.
Summary and next steps

- US leadership in the area of fusion S&E is decreasing due to reduced budgets, international collaboration is more needed than ever
- Several S&E gaps remain in the pathway to DEMO that will not be fully addressed by ITER
- Under the scope of FNSF we are mainly working on:
  - Safety code development
  - Accident identification and analysis
  - Material and component testing
  - Remote handling approaches
- Important challenges remain for FNSF and beyond:
  - Source term characterization and behavior during accidents
  - Routine releases
  - Waste management issues
- Look forward to further discussions with all of you during this meeting
FNSF is very different from ITER (and a demonstration power plant)

- The neutron exposure of materials is \( \approx 30 \times \) higher
- The materials are all different, except for tungsten
- The structures surrounding the plasma will operate at \( \geq 3 \times \) higher temperatures
- Tritium is bred in the FNSF, not purchased like ITER
- The plasma is “on” making neutrons for \( 7 \times \) longer per year, and plasma pulses are \( 1000 \times \) longer
- Maintenance of the fusion core is few-large-pieces, not by blanket module….and there are others

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>FNSF</th>
<th>Power Plant, 1000 MW_e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron exposure life of plant</td>
<td>0.3, 3.0</td>
<td>8.5, 85</td>
<td>60-98, 600-980</td>
</tr>
<tr>
<td>Neutron life of plant, MW-yr/m², dpa</td>
<td>316SS, CuCrZr, Be, W, H₂O, SS304, SS430</td>
<td>RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel</td>
<td>RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel</td>
</tr>
<tr>
<td>Operating temperature, °C</td>
<td>100-150</td>
<td>400-600</td>
<td>600-700</td>
</tr>
<tr>
<td>Tritium breeding ratio</td>
<td>( \sim 0.003 )</td>
<td>( \sim 1.0 )</td>
<td>1.05</td>
</tr>
<tr>
<td>Plasma on-time in a year, %</td>
<td>5</td>
<td>( \sim 10-35 )</td>
<td>85</td>
</tr>
<tr>
<td>Plasma pulse duration, s</td>
<td>500-3000</td>
<td>( \sim 10^6 ) (2 weeks)</td>
<td>2.7x10^7 (10.5 months)</td>
</tr>
</tbody>
</table>
# FNSF mission scopes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>minimal</th>
<th>moderate</th>
<th>maximal</th>
<th>Power plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant DT operations</td>
<td>~ 15 yr</td>
<td>~ 25 yr</td>
<td>~ 35 yr</td>
<td>47 yr (40 FPY)</td>
</tr>
<tr>
<td>Peak neutron wall load, MW/m²</td>
<td>1.0</td>
<td>1.5</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Plasma on-time per year</td>
<td>10-35%</td>
<td>10-35%</td>
<td>10-45%</td>
<td>85%</td>
</tr>
<tr>
<td>Max dpa on first wall (or max dpa to replace)</td>
<td>5 -18,36</td>
<td>7 - 37,74</td>
<td>10 - 70,140</td>
<td>150-200</td>
</tr>
<tr>
<td>Q\textsubscript{engr}</td>
<td>&lt;&lt; 1</td>
<td>&lt; 1</td>
<td>&gt; 1</td>
<td>4</td>
</tr>
<tr>
<td>Tritium breeding ratio</td>
<td>&lt; 1</td>
<td>~ 1</td>
<td>&gt; 1</td>
<td>1.05</td>
</tr>
<tr>
<td>Plant life, peak dpa</td>
<td>32, 50</td>
<td>88, 126</td>
<td>202, 274</td>
<td>765</td>
</tr>
<tr>
<td>TF/PF magnet</td>
<td>Cu</td>
<td>LTSC or HTSC</td>
<td>LTSC or HTSC</td>
<td>LTSC or HTSC</td>
</tr>
<tr>
<td>Vacuum vessel material</td>
<td>SS</td>
<td>Bantitic steel</td>
<td>Bantitic steel</td>
<td>Bantitic steel</td>
</tr>
<tr>
<td>Divertor</td>
<td>W/CuCrZr/H₂O</td>
<td>W/W/He</td>
<td>W/W/He</td>
<td>W/W/He</td>
</tr>
</tbody>
</table>
Materials testing in FNSF vs HFIR, SNS and IFMIF

![He/dpa ratio graph]

<table>
<thead>
<tr>
<th>Irradiation Facility</th>
<th>FNSF</th>
<th>HFIR</th>
<th>SNS (sample @ 3 cm)</th>
<th>SNS (sample @ 5 cm)</th>
<th>IFMIF (high flux test module)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of neutrons with E &gt; 0.1 MeV</td>
<td>~75%</td>
<td>~24%</td>
<td>~65%</td>
<td>~65%</td>
<td>96%</td>
</tr>
<tr>
<td>F82H or EUROFER</td>
<td>10 (low)</td>
<td>0.3 (high)</td>
<td>74 (low)</td>
<td>20 (high)</td>
<td>13</td>
</tr>
<tr>
<td>W</td>
<td>0.6 (low)</td>
<td>0.0008 (high)</td>
<td>?</td>
<td>?</td>
<td>4 (high)</td>
</tr>
<tr>
<td>SiC</td>
<td>95 (low)</td>
<td>1.7 (low)</td>
<td>98 (low)</td>
<td>37 (low)</td>
<td>150 (high)</td>
</tr>
</tbody>
</table>

Much softer spectrum in HFIR compared to fusion. (No neutrons above 10 MeV)

Highly energetic neutrons ($E_n$ up to 300 MeV) and protons ($E_p$ up to 1000 MeV) in SNS

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# Data provided by J. Knaster (IFMIF project leader), May 2015.