Fusion Nuclear Science Facility, Motivation and the Program to Develop a Basis for Power Plants

C. E. Kessel, PPPL


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The Fusion Energy Systems Studies Team is Examining the Fusion Nuclear Science Facility

What does an FNSF have to accomplish?

How do we measure the FNSF progress for fusion development?

How does the FNSF accomplish its mission?

What is the pre-requisite R&D needed for an FNSF? What does the FNSF require from our program to succeed?

How does an FNSF fit in the larger fusion development program?

What critical insights about this facility can be uncovered, impacts of assumptions, technical choices and philosophies, ...?
The FNSF is the First Step in a Two-Step Pathway to Commercial Fusion Power Plants

- **First strongly burning plasma**
  - **ITER**
  - **FNSF**
  - **DEMO**
  - **Power Plant**

- **Max neutron damage**
  - 3 dpa
  - 37-74 dpa
  - 100-150 dpa
  - 150+ dpa

- **Max plasma pulse**
  - 500-3000s
  - 1-15 days
  - 15-365 days
  - 365+ days

- **TBR**
  - ~0
  - ~1.0
  - 1.05+

- **T_{blanket}, T_{cool, exit}**
  - 285C, 150C
  - 550C, 650C
  - 550C, 650C

- **Materials**
  - 316SS, CuCrZr, Be, W, H₂O, SS304, SS430
  - RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel

- **Demonstrate routine power plant operations**
  - No technical gaps

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316SS, CuCrZr, Be, W, H₂O, SS304, SS430

RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel
The FNSF is the First Step in a Two-Step Pathway to Commercial Fusion Power Plants

Fusion nuclear break-in

ITER

FNSF

mod

max

min

FNSF

Power Plant

Routine electricity production

Largely the same starting point based on proposed facilities

Additional R&D on DEMO

To have no technical gaps from DEMO to a PP

Additional R&D on DEMO

To have no technical gaps from DEMO to a PP
What is a Possible Time-Frame and Where Does the FNSF Reside*?

- Present and near term confinement devices, short pulse → to long pulse

* US does not presently have a commitment to design and construct the FNSF or DEMO
The FNSF **IS NOT** a Power Plant

**BUT**, its program is designed to establish the “database” for DEMO and subsequent power plants...it combines research, development, and demonstrations

The FNSF has a multi-faceted purpose to break-in to the fusion nuclear regime

1) Perform the materials research within the nuclear fusion in-service environment

2) Establish the operation of fusion core components (made of these materials) over the prototypical range of environmental parameters (T, pressure, hydrogen, etc.) with fusion neutrons

3) Establish the operation of multiple subsystems/functions critical to fusion, such as tritium breeding, recovery, control, fueling, exhaust, and storage.....others include power handling, maintenance, measurements, fusion enabling technologies, etc.

4) Establish the ultra-long plasma pulses, with high performance, sustained by a range of plasma enabling technologies

**Power Plant Relevance** is critical to the FNSF, to prepare for future device’s operating regimes and to provide a **comprehensive experiment** on the fusion core and ex-core
The pre-FNSF Component Development and Phased Operation on the FNSF are Essential for Success

On the FNSF we will have some failures, but the presence of constant failures are incompatible with the plasma-vacuum systems and the need for radioactive materials remote handling

We will use a high level of pre-qualification of materials and components

We will test all materials in the fusion core up to the anticipated dpa level before operating to that dpa level on the FNSF, with fission and fusion relevant neutron exposures

We will test the most integrated prototype possible of blanket, divertor, and launcher components before installation, in a non-nuclear integrated facility

On the FNSF, the phases ramp up the operating parameters slowly to provide monitoring

The plasma durations, duty cycles, dpa’s, and operating temperatures are advanced through the 1 DD, and 5 DT program phases

Inspections and autopsy of components is used to monitor evolution of materials, requiring highly efficient hot cell turn-around, during any given phase and at the end of a phase

Test blanket modules will be used for a “look forward”, engineering testing, backup blanket concepts, and material sample testing
Missions of the FNSF, Using Metrics to Show How Much Progress We Are Making to Address Them

Strongly advance fusion neutron exposure of fusion core (ex-core) components toward power plant levels

Utilize and advance power plant relevant materials

Operate in power plant relevant fusion core environment (T, p, v, B, etc.)

Produce tritium in required quantities, compensating consumption, decay and losses

Extract, process, inject, and exhaust tritium in manner that meets all safety criteria, and high level of prediction, control and accountancy

Routinely operate very long pulse plasmas, longer or long enough to access required phenomena, with sufficient plasma performance

Advance and demonstrate enabling technologies

Demonstrate safe and environmentally friendly plant operations (tritium leakage, hot cell operations, radioactive material handling, etc.)

Develop power plant relevant subsystems for robust and high efficiency operations

Advance toward high availability, reliability, efficient maintenance operations, etc.
## Sampling of Metrics for Some Missions

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>FNSF</th>
<th>DEMO</th>
<th>Power Plant ARIES-ACT1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Strongly advance the fusion neutron exposure.....</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life of plant peak FW fluence, MW-yr/m² (life of plant)</td>
<td>0.3</td>
<td>12.6</td>
<td></td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(8.4 FPY)</td>
<td></td>
</tr>
<tr>
<td>Peak FW fluence to replace blanket, MW-yr/m² (dpa) (replacements)</td>
<td>0.3</td>
<td>0.7, 1.9, 2.6, 3.7, 7.4</td>
<td>15-20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(7.19, 27, 37, 74)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3)</td>
<td>(5)</td>
<td></td>
<td>(150-200) (4-6)</td>
</tr>
<tr>
<td></td>
<td>(0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak FW neutron wall load, MW/m² (average)</td>
<td>0.76</td>
<td>1.75</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.56)</td>
<td>(1.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4. Produce tritium in quantities that.....</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TBR - total</td>
<td></td>
<td>1.06*</td>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td>Tritium produced per year, kg</td>
<td>0.004</td>
<td>10.7</td>
<td>101-146</td>
<td></td>
</tr>
<tr>
<td>Li-6 enrichment</td>
<td></td>
<td>90%</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>OB FW hole/loss fraction</td>
<td></td>
<td>7-9%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td><strong>6. Routinely operate very long plasma durations....</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma on-time per year (ave)</td>
<td>5%</td>
<td>35%</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>Plasma pulse duration, s</td>
<td>500-3000</td>
<td>1.2x10⁶</td>
<td>2.7x10⁴</td>
<td></td>
</tr>
<tr>
<td>Plasma duty cycle</td>
<td>25%</td>
<td>95%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>βq H₉₈ / q₉₅</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4-2.1</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>5-10</td>
<td>4-6</td>
<td>25-48</td>
<td></td>
</tr>
<tr>
<td>f₉₅</td>
<td>0.25-0.5</td>
<td>0.52</td>
<td>0.77-0.91</td>
<td></td>
</tr>
<tr>
<td>Pcore_rad / (Palpha + Pan)</td>
<td>0.27</td>
<td>0.24</td>
<td>0.28-0.46</td>
<td></td>
</tr>
<tr>
<td>Pdiv_rad / Psol</td>
<td>0.7</td>
<td>0.75-1.0</td>
<td>0.75-1.0</td>
<td></td>
</tr>
</tbody>
</table>

*depending on assumed H/CD systems
Why Pursue a Smaller First Step, like the FNSF?

Untested regime of fusion neutrons on multi-materials under multi-factor environment

Fission experience with materials (learned from PWR and breeder development programs)

- Extreme sensitivity of swelling with temperature
- Impacts of irradiation dose rate increased hardening and threshold for swelling
- Impacts of smaller constituents ~ 0.5 wt% can lead to positive and negative effects
- Surface conditions, welds, and metallurgic variability provided wide variations in irradiation behavior
- Incubation periods that delay the emergence of a phenomena
- Simultaneous multiple variable gradients (neutron fluence, temperature, stress) on crack behavior
- Radiation induced segregation, precipitation, modified thermal precipitation
- ......

Goal is to establish the actual fusion in-service material and scientific/engineering database on all components in the fusion neutron environment and in the overall environment before moving to larger size and electricity production

This is NOT the same database that we used to pursue the FNSF, it replaces/augments it
The smaller intermediate step (FNSF) on a path to power plants → what comes before FNSF

Neutron irradiation of individual materials in 1) fusion relevant neutron source, 2) fission reactor and doping, 3) ion bombardment

Tritium science

(LiPb) Liquid metal science

Enabling technologies

Prototypical parameters & integration

Integrated diagnostic testing

Integrated diagnostic testing

Integrated blanket component testing & ITER TBM progress (weak nuclear)

Non-nuclear

Integrated launcher/guide testing

Plasma facing components/plasma material interactions in 1) tokamaks, 2) linear plasma devices, 3) offline (e.g. HHF, liquid metal)

Plasma facing components/plasma material interactions in 1) tokamaks, 2) linear plasma devices, 3) offline (e.g. HHF, liquid metal)

Plasma development in 1) short pulse tokamaks, 2) long pulse tokamaks (EAST, KSTAR, JT-60SA), 3) ITER
The smaller intermediate step (FNSF) on a path to power plants → what is unique about the FNSF

The environment in the FNSF will not have been seen before, the combination of fusion neutrons and the multi-physics non-nuclear environment

Helium production (appm) for 100 dpa at plasma facing side

Temperatures: Deg C
- 543 C
- 350 C
- 94 MPa

Von Mises stress

LiPb, ~3MPa

He, 8 MPa

Y. Huang, N. Ghoniem, UCLA

H. Tanigawa, E. Wakai 2012
“Several critical materials behaviors led to major disturbances in the development program for the liquid metal fast breeder” (Bloom et al, JNM 2007 & Was, JNM 2007)

Environment:
- Temperature
- Stress
- Damage and He/H generation
- Hydrogen in matrix (H and T)
- LiPb/RAFM interface (T,v), chemical
- LiPb/SiC-c FCI interface (T,v), chemical
- B-field from 5-12 T, OB to IB for LiPb
- Heating (surface and volumetric)

GRADIENTS in all of the above parameters

LM estimated corrosion for a DCLL
Smolentsev, UCLA

Wall thinning
- 0-10 μm/yr
- 10-20 μm/yr
- 20-30 μm/yr
- 30-40 μm/yr
The Plasma Durations Required in the FNSF is a Large Leap Compared to Present/Planned Tokamaks

Before the FNSF, must combine
- ultra-long pulse linear plasma facilities
- tokamak confinement experiments at shorter pulses
- high heat flux facilities
- advanced predictive simulation capability

Take advantage of the DD phase of FNSF to extend pulse lengths
Physics Strategy for the FNSF Regime of long pulse, 100% non-inductive, burning plasma

Pursue $\beta_N \leq$ no wall limit to accomplish mission, but install appropriate feedback or other capability to exceed no wall limit $\rightarrow$ by how much?

Install passive stabilizers and feedback coils to provide higher plasma elongation, significantly expanding operating space, and $A = 4$

Operate below the Greenwald density limit $n/n_{Gr} \leq 1$, but not rely on low values to enhance CD

Plasma current is driven 100% non-inductively in flattop, however, a solenoid provides rampup assistance and flattop feedback...examining NB, LH, IC and EC

Peak heat flux tolerated in the divertor $\leq 10$ MW/m$^2$, while pursuing high heat flux design/material solutions and 2D SOL/divertor plasma simulations

Pursuing high toroidal field in the plasma, targeting LTSC advances
Plasma *Performance and Duration* in DIII-D and JT-60U
Looking at Experiments for Guidance

<table>
<thead>
<tr>
<th></th>
<th>JT-60U</th>
<th>JT-60U</th>
<th>DIII-D</th>
<th>DIII-D</th>
<th>DIII-D</th>
<th>DIII-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_N$</td>
<td>2.4</td>
<td>1.7</td>
<td>3.5*</td>
<td>$\geq$ 3.5</td>
<td>2.0</td>
<td>3.1-3.4*</td>
</tr>
<tr>
<td>$\tau_{\text{flattop}}/\tau_{\text{CR}}$</td>
<td>2.8</td>
<td>2.7</td>
<td>2.0</td>
<td>$\sim$ 1.5</td>
<td>$&gt; 2$</td>
<td>$\sim 0.4-1.0$</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>4.5</td>
<td>$\sim$ 8</td>
<td>6.7</td>
<td>5.5-6.5</td>
<td>4.7</td>
<td>5.0-5.5</td>
</tr>
<tr>
<td>$f_{\text{BS}}$</td>
<td>45%</td>
<td>80%</td>
<td>40-50%</td>
<td>50-60%</td>
<td></td>
<td>$\sim$ 60%</td>
</tr>
<tr>
<td>$f_{\text{NI}}$</td>
<td>90%</td>
<td>100%</td>
<td>75%</td>
<td>$\sim$ 100%</td>
<td>80-100%</td>
<td></td>
</tr>
<tr>
<td>$H_{98}$</td>
<td>1.0</td>
<td>1.7</td>
<td>1.0</td>
<td>1.6</td>
<td>1.3</td>
<td>$\geq$ 1.2-1.3</td>
</tr>
<tr>
<td>$q_{\text{min}}$</td>
<td>$\sim$ 1.5</td>
<td></td>
<td>1.5</td>
<td>$\sim$ 1.0</td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>$\sim$ steady state</td>
<td>steady state</td>
<td>$\rightarrow$ steady state, off-axis NB</td>
<td>$\rightarrow$ SS hybrid, hi rot</td>
<td>QH-mode, no ELMs</td>
<td>steady state</td>
</tr>
</tbody>
</table>

**EAST and KSTAR will soon contribute**

*utilize active error field correction, plasma rotation, $\beta_N \sim 1.15 \times \beta_N^{\text{no wall}}$

Additional experiments on JT-60U, DIII-D, AUG have 1) approached and exceeded **density limit**, 2) **high radiated power** in the plasma and divertor, 3) avoiding or actively **suppressed NTMs**, 4) **low plasma rotation**, and 5) **PFC materials**
Systems Code Identification

<table>
<thead>
<tr>
<th>$A = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, m</td>
</tr>
<tr>
<td>$\kappa_X$, $\delta_X$</td>
</tr>
<tr>
<td>$l_p$, MA</td>
</tr>
<tr>
<td>$B_T$, $B_T^{\text{coil}}$, $T$</td>
</tr>
<tr>
<td>$\langle j_{TF} \rangle$, MA/m$^2$</td>
</tr>
<tr>
<td>$\beta_N^{\text{th}}$, $\beta_N^{\text{fast}}$</td>
</tr>
<tr>
<td>$q_{95}$</td>
</tr>
<tr>
<td>$H_{98}$</td>
</tr>
<tr>
<td>$f_{BS}$</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
</tr>
<tr>
<td>$n/n_{\text{Gr}}$</td>
</tr>
<tr>
<td>$n(0)/\langle n \rangle$, $T(0)/\langle T \rangle$</td>
</tr>
<tr>
<td>$P_{\text{fusion}}$, $P_{\text{rad,core}}$, $P_{\text{rad,div}}$, $P_{\text{aux}}$, MW</td>
</tr>
<tr>
<td>$Q$, $Q_{\text{engr}}$</td>
</tr>
<tr>
<td>$\eta_{\text{CD}}$, A-m$^2$/W</td>
</tr>
<tr>
<td>$\langle N_w \rangle$, $N_w^{\text{peak}}$, MW/m$^2$</td>
</tr>
<tr>
<td>$q_{\text{div}}^{\text{peak}}$ (OB, IB), MW/m$^2$</td>
</tr>
</tbody>
</table>

Large scans over $R$, $B_T$, $q_{95}$, $\beta_N$, $Q$, $Z_{\text{eff}}$, $n/n_{\text{Gr}}$

$\langle j_{TF} \rangle = 15$ MA/m$^2$

$f_{\text{div,rad}} = 90\%$ ($\lambda_{\text{pow}}^{\text{Fundamenski}}$)

Filters for solutions

$\beta_N \leq 2.6^*$

$q_{\text{div}}^{\text{peak}} \leq 10$ MW/m$^2$

$N_w^{\text{peak}} \geq 1.5$ MW/m$^2$

$B_T^{\text{coil}} \leq 16$ T (adv-LTSC)

IB Radial build from neutronics:

$\Delta_{FW/\text{blkt}} = 50$ cm

$\Delta_{SR} = 20$ cm

$\Delta_{VV} = 10$ cm

$\Delta_{LT\text{ shield}} = 23$ cm

$\Delta_{\text{gaps}} = 20$ cm

*examining benefits of feedback to raise this toward 3.0-3.2
What is the reliably achievable radiated power fraction in the divertor?

We assume a radiated power fraction $P_{\text{div,rad}}/P_{\text{SOL}}$ of 90% in systems analysis.

Fully detached radiates ~ 100%
ITER-like divertor radiates ~ 75%
Several Engineering Decisions

Low temperature superconducting coils, advanced Nb$_3$Sn, with design upgrades to winding pack, a watch on HTSC, probably using HTSC for CS

Helium cooling in blanket, shield, divertor, and vacuum vessel, NO WATER inside or in VV, only outside VV

Focus on DCLL blanket concept with backup concepts (HCLL, HCCB/PB)

Net electricity is NOT a facility target, but electricity generation can be demonstrated

WC used as shielding filler on IB in structural ring, VV and low temperature shield, B-FS used for OB, LOCA analysis showed that WC was OK

Horizontal maintenance is adopted, single sectors are removed and replaced (1/16$^{th}$), superstructure support on TF coil large outer leg

Used lower irradiation limits on TF coil than typical for power plant studies

Placed 200 micrometers of W on the FW for erosion and transients (ELMs & disruption), while trying to optimize design for maximum heat flux

Assume concentric He and LiPb piping from fusion core to HX

Plate divertor concept is tungsten (something) structural and armor material, adv-RAFM for cold leg structure, uncertainty on the form of W
Program on the FNSF – what is this device actually doing?

<table>
<thead>
<tr>
<th>Phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>He/H</td>
<td>DD</td>
<td>DT</td>
<td>DT</td>
<td>DT</td>
<td>DT</td>
<td>DT</td>
</tr>
<tr>
<td>years</td>
<td>1-2</td>
<td>2-3</td>
<td>2.75</td>
<td>4.5</td>
<td>5.0</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$N_{w,\text{peak}}$, MW/m$^2$</td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
<td>2.25</td>
<td></td>
</tr>
<tr>
<td>Plasma on-time, %/year</td>
<td>15-50</td>
<td>15</td>
<td>25</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>55 d</td>
<td>91 d</td>
<td>128 d</td>
<td>128 d</td>
<td>128 d</td>
<td>310 d</td>
<td></td>
</tr>
<tr>
<td>Plasma duty cycle, % (pulse/dwell)</td>
<td>33</td>
<td>67</td>
<td>91</td>
<td>95</td>
<td>95</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1d/2d)</td>
<td>(2d/1d)</td>
<td>(5d/.5d)</td>
<td>(10d/.5d)</td>
<td>(10d/.5d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total maintenance time, days</td>
<td>550 d</td>
<td>1131 d</td>
<td>1120 d</td>
<td>1495 d</td>
<td>1495 d</td>
<td>2585 d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 d/yr</td>
<td>229 d/yr</td>
<td>224 d/yr</td>
<td>230 d/yr</td>
<td>230 d/yr</td>
<td>55 d/yr</td>
<td></td>
</tr>
<tr>
<td>Peak dpa</td>
<td>7.2</td>
<td>19.7</td>
<td>30.6</td>
<td>39.8</td>
<td>79.6</td>
<td>150-200</td>
<td></td>
</tr>
<tr>
<td>Max/min blanket structure op temp, °C</td>
<td>&gt;400</td>
<td>&gt;400</td>
<td>550/400</td>
<td>550/400</td>
<td>600/450</td>
<td>650/500</td>
<td>650/500</td>
</tr>
<tr>
<td>Blanket Structure material</td>
<td>RAFM</td>
<td>RAFM</td>
<td>RAFM</td>
<td>RAFM-ODS</td>
<td>RAFM-ODS(NS)</td>
<td>RAFM-ODS(NS)</td>
<td>RAFM-ODS(NS)</td>
</tr>
</tbody>
</table>
The FNSF Program is being studied further to address a range of issues

1) Can the DD Phase provide enough discharge time ranging from 1hr to 10 day pulse lengths, likely will utilize higher diagnostic coverage

2) Provide higher or lower neutron wall loads would result in short or longer time to reach a dpa level, e.g. operate above the no-wall beta limit

3) Varying operating temperatures of the DT phases may require BOTH faster coolant flow and lower fusion power, longer time to reach dpa target, constrained by blanket design thermo-mechanics

4) Desire to reach longest plasma durations early in the program, rather than spend the whole program progressively extending the plasma pulse length...appears a discharge sequence can achieve this, and still arrive at ~7 dpa at the end of the phase

5) Examine maintenance times associated with specific tasks (planned maintenance)
   - Ex-vessel inspection
   - In-vessel inspection
   - Minor maintenance ex-vessel
   - Minor maintenance in-vessel
   - Major ex-vessel
   - Major in-vessel maintenance (sector removal or 16 sector removal)

   Contingency for unplanned maintenance
Challenges in Creating a Program on the FNSF

Flexibility in adjusting environmental parameters like temperature, for example
  - Want to examine a range of temperatures to uncover phenomena
  - Blanket designs are generally optimized and therefore constrained
  - Use fusion power, flow speed and inlet temperature (for example), but range is likely limited
  - Similar for Launchers and divertors

*What is the flexibility to explore the operating regime?*

How is information obtained from failures, material inspections, and operations, used to correct, re-design, and re-manufacture components or other systems for the next (?) phase....can time-scales be minimized

The procedures of stopping the plasma, 1) but maintaining components at temperature, 2) removing a single sector while others are warm, ....ultimately for describing material history

Do we need allocate larger time, more in the inspection/maintenance category, to autopsy and process results, the samples are highly radioactive, but we can not wait years to find out what happened

*The Hot Cell becomes a critical part of the FNSF facility, where sectors are inspected, decontaminated, dismantled and ultimately turned into samples for examination*
Components in fusion core would be evolved and tested in the FNSF

We concentrate on the blankets, but there are others that may have a testing sequence…..materials, temperatures, design, etc.
Blanket Layout and Testing

There are several DIFFERENT blanket geometries due to multiple functions in the FNSF

**DCLL 550/400C RAFM** (some are taken for autopsy) 4

- DCLL 550/400C RAFM/ LH 1
- DCLL 550/400C RAFM/ EC 1
- DCLL 550/400C RAFM/ NB 1
- DCLL 550/400C RAFM/ IC 1

- DCLL 600/450C RAFM ODS *(next phase T and RAFM)* 2
- DCLL 550/400C RAFM/ MTM 1
- DCLL 550/400C RAFM/ TBM-HCLL 1
- DCLL 550/400C RAFM/ TBM-HCCB(PB) 1
- DCLL 550/400C RAFM/ Diagnostic 3

A. Davis, UW

---

Nuclear analysis of different sectors

Step 9
4 TBM added, 4

Step 10
3 Diagnostics added, 3

Step 11
2 NBI added, 4

Step 12
1 IC added, 1

Step 13
1 LH added, 1

Step 14
1 EC added, 1

Top view
Divertor Testing, must fit into the allocated envelope

What will be the preferred W or other divertor material?
- W or W-alloy
- W/X composites
- $W_t/W_m$ composites

Will there be variants like RAFM?
Structure & armor design
Magnetic geometries
Temperature ranges

 Taken from Snead, 2016

W/RAF laminate (Garrison)
FZJ
WC in Fe matrix (Álvarez et al., 2015)

Flat plat fully detach
$F_{div,rad} \sim 100\%$

X-divertor, KDEMO
Covelle, Univ Texas

ITER-like tilted plate
$F_{div,rad} \sim 75\%$
What do we do with the Sectors: Blankets, Divertors, Launchers in the Hot Cells?

Inspect
Decontaminate (clean off)
Inspect
Dismantle
Inspect
Examine untreated surfaces
Examine mounts/connectors

**Cut samples**
- FW
- Side wall
- Grid plates
- Mounting hardware
- SR
- Div armor
- Div structure
- FCI
- W stabilizer

......

Material examinations (PIE, mech prop tests, He bubbles, etc.)

Also examine the test specimens in the material test module & surveillance samples
Hot Cell

We are anticipating a hot cell sequence from large intact sectors progressively down to small material samples, requiring a transfer from hot cell 1 to hot cell 2, etc.

Robotic and computer controlled systems would likely dominate the processing

Issues include 1) high dose and hardened equipment, 2) complex processing (tritium, surface materials), 3) decay heat, and 4) need for rapid turnaround
**Pre-FNSF R&D** Major Topics and Evolution Toward FNSF

<table>
<thead>
<tr>
<th>2015</th>
<th>2025</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>single-few effects</td>
<td>partial integration expts</td>
<td>maximum integration expts</td>
</tr>
<tr>
<td><strong>Fusion neutron material science</strong></td>
<td><strong>Accelerator based facilities</strong></td>
<td><strong>Fusion neutron and integrated component testing facilities continue to operate in parallel with FNSF</strong></td>
</tr>
<tr>
<td><strong>Tritium science</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Liquid metal breeder science</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Plasma-material science</strong></td>
<td><strong>Integration of FW/blanket</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Linear Plasma &amp; Tokamaks &amp; Offline</strong></td>
<td></td>
<td><strong>Early DD phase of FNSF</strong></td>
</tr>
<tr>
<td><strong>Enabling technologies (H/CD, fueling, pumping, .....</strong></td>
<td><strong>Predictive Simulation Development</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Pre-FNSF R&D Major Topics and Evolution Toward FNSF

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2025</th>
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<tbody>
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<td>Topics</td>
<td>single-few effects</td>
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<td>maximum integration expts</td>
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</table>

How do I turn these TOPICS into a concrete set of experiments that get me to the FNSF?

Integrate and make prototypical

### Fusion

- Predictive Simulation Development

### Tritium

### Liquid Metal Breeder

### Plasma-material

### Nuclear Science Facility

### Enabling technologies (H/CD, fueling, pumping, ....)
Zoom–In: *Tritium Science* Breakdown

2015
- single-few effects

2025
- partial integration expts
- maximum integration expts

2035
- Plasma tritium implantation/permeation/retention
- Tritium behavior in materials and multi-materials
- Tritium extraction from LiPb breeder
- Tritium breeding/extraction fission integrated expt

Predictive Simulation Development

Integration of FW/blanket
Plasma tritium implantation/permeation/retention

- PISCES at UCSD and TPE at INL, existing expts
- Characterize its parameters relative to a FNSF or DEMO (particle energies, fluxes, particle species and mixtures, operating temperatures, testing duration, in-situ surface diagnostics, etc.)
- Capability to test He cooled component geometry, testing irradiated samples
- In-situ measurements in long pulse tokamaks

Tritium extraction from LiPb breeder

- No facility at present (do with deuterium as much as possible?)
- Requires a LiPb loop, running through a tubular test removal apparatus
- Artificially introduce deuterium, and control/characterize LiPb material
- Must test different permeation window materials (group 5, modified group 5 as noted by INL)
- Parameters include operating temperature, flow rates, hydrogen concentrations, impurities in LiPb, etc.
- Scale-up to multi-tube
Tritium behavior in materials and multi-materials

- Testing apparatus for single materials (solids) characterizing with He at 8 MPa, vacuum, LiPb at ~ 3 MPa
- LiPb pristine, and LiPb with He bubbles, intermetallics, corrosion products
- at representative tritium/deuterium concentrations
- at temperatures, tending toward service environment
- accurate surface condition characterization
- irradiated materials
- RAFM/LiPb, RAFM/SiC-c/LiPb multi-material tests

These experiments lead into the integrated blanket testing facility

Tritium breeding/extraction fission integrated expt

Using fission facility to access larger volume for testing
Create a series of test articles that include RAFM steel, SiC-c, flowing He, and LiPb

Stationary LiPb
Flowing LiPb

Tests of dpa (exposure), Li6 for tritium behavior, temperature, flow rates for LiPb
Zoom-In: Fusion Neutron Material Science

2015

- Single-few effects

2025

- Partial integration expts

2035

- Maximum integration expts

This R&D generally does NOT integrate significantly

Fusion neutrons materials science

Accelerator based facilities

Non-nuclear material characterization and industrial production

Fission neutron, ion and doping material exposure

HFIR, ATR

SNS, LANSCE, US
SINQ, DONES, EU
A-FNS, JA

Multi-material/environment fission neutron exposure

HFIR, ATR

Fusion relevant neutron material exposure

Predictive Simulation Development
Pre-FNSF: Fusion Nuclear Materials Science, how do we see providing tested materials in the form of components to the FNSF

- 2020
  - Non-nuclear characterization
  - Fission, ion and doping irradiations
  - Fusion relevant neutron irradiations
  - Industrial/manufacturing
  - Material/environment match

- 2030
  - Pre FNSF RAFM-1 development
  - Pre FNSF RAFM-2 development
  - Pre FNSF RAFM-3 development
    - Pre FNSF RAFM-4 development
  - Pre FNSF FCI/SiC-c-1 development
    - Pre FNSF FCI/SiC-c-2 development
  - Pre FNSF bainitic development (VV)
  - Pre FNSF tungsten-1 development
  - Pre FNSF tungsten-2 development

- 2040
  - Pre FNSF RAFM-2 development
  - Pre FNSF RAFM-3 development

- 2050
  - Pre FNSF RAFM-3 development
  - Pre FNSF FCI/SiC-c-2 development
  - Pre FNSF bainitic development (VV)
  - Pre FNSF tungsten-1 development

- 2060
  - Pre FNSF RAFM-4 development
  - Pre FNSF FCI/SiC-c-2 development
  - Pre FNSF bainitic development (VV)
  - Pre FNSF tungsten-2 development

He/DD, DT, FNSF
- 7 dpa
- 19 dpa
- 30 dpa
- 40 dpa
- 40-80 dpa

- US DEMO

What type of database is required for FNSF? Scientific or engineering?

A quantitative analysis of a single blanket concept could make the urgency case for getting to fusion relevant neutrons NOW

- # of samples of mech type
- # temperatures
- # materials
- Test vol
- Dpa/FPY
- Availability
Starting point for organizing the pre-FNSF: PFC/PMI science area from the FNSF perspective

SOL plasma experiments/diagnostics
Divertor plasma experiments/core coupling

Establish “translation” of linear results to tokamaks
Plasma material interaction/linear/ultra-long duration

Loading conditions
Materials science and PFC component development

High heat flux simulators (ebeams, lasers, flashlamps, etc.)
Liquid metal test stands, plasma/vacuum, LM properties, flow, geometry, LM species, substrate design and fabrication, etc

Solid materials science, PFC component design and fabrication

SOL/divertor plasma simulations
Zoom–In: *Enabling Technology* Breakdown

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</tbody>
</table>

- LTSC advance/optimize, HTSC development
- Pellet fueling, exhaust and continuous vacuum pumping
- Heating and current drive sources, launchers, transmission, coupling
- Diagnostics for FN regime, physics and engineering
- Heat exchanger development
- Tritium processing for breeding and fueling cycles, storage
- Hot Cell handling, processes, PIE

...
Detailed Analysis in Engineering and Physics of the FNSF

**Neutronics**, 1D this year to develop builds and heating, 3D next year for more accuracy, streaming and other issues (A> Davis, L. El-Guebaly, UW)

**Liquid metal MHD** analysis by Smolentsev (UCLA) on IB and OB LiPb flow

**Thermo-mechanics of blanket, FW and divertor** by Y. Huang/N. Ghoniem (UCLA), J. Blanchard at UW, **S. Malang** (retired), M. Tillack (UCSD)

**TF coil (and PF) coils** stress analysis and winding pack design by **Y. Zhai**, P. Titus (PPPL)

**Tritium inventory, extraction** analysis (and accident) by **P. Humrickhouse** (INL)

**Materials science development and assessments** by FusMat group at ORNL (A. Rowcliffe, L. Garrison, and Y. Katoh)

**CAD**, establishing layouts for FNSF from systems code and design activities (E. Marriott)

**Maintenance, hot cell, layout** (L. Waganer)

**Core plasma** equilibrium, ideal stability, time-dependent transport evolution, H/CD (C. Kessel, PPPL)

**SOL/divertor analysis**, (Rognlien and Rensink, LLNL)

**RF requirements** (**G. Wallace** and S. Wukitch, MIT/PSFC)
The FNSF Has a Unique Role to Play in Breaking in to the Fusion Nuclear Regime

Introduces the combined fusion nuclear and multi-physics non-nuclear environment on fusion core not seen before

Advances the multiple missions required to reach a power plant operating space

Operates a wide range of enabling technologies (in-VV, ex-VV...)

Develops the ultra-long plasma durations, plasma support technologies, and plasma performance for the strong fusion nuclear regime

A careful and deliberate step is required for this challenging leap

The FNSF is a combination of discovery and demonstration, and ultimately provides the database required to pursue fusion energy based power plants
BACKUP SLIDES
Nuclear Analysis

TBR with all penetrations: 1.067

TBR with each penetration type:

A. Davis, UW

NWL map

3D CAD, LH launcher

Neutron heating

Dpa/FPY
<table>
<thead>
<tr>
<th></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</td>
<td>5 - 18,36</td>
<td>7 - 37,74</td>
<td>10 - 70,140</td>
<td>150-200</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_{ener}</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>50</td>
<td>126</td>
<td>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>Baintic steel</td>
<td>Baintic steel</td>
<td>Baintic 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>
## Systems analysis of Min and Max FNSF

$q_{\text{div, peak}} < 10 \text{ MW/m}^2$

$\beta_N^\text{total} < 0.026$

$B_T^\text{coil} \leq 16 \text{ T}$

$\eta_{\text{CD}} = 0.2 \text{ A/W-m2}$

Same plasma shape

$f_{\text{div,rad}} = 0.9$

Smallest radius with a robust op space

<table>
<thead>
<tr>
<th>FNSF</th>
<th>Min</th>
<th>Mod</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R, \text{ m}$</td>
<td>3.5</td>
<td>4.8</td>
<td>5.8</td>
</tr>
<tr>
<td>$I_p, \text{ MA}$</td>
<td>6.38</td>
<td>7.87</td>
<td>8.04</td>
</tr>
<tr>
<td>$B_T, B_T^\text{coil}, &lt;j_{\text{TF}}&gt;$</td>
<td>5.75, 13.5, 14.7</td>
<td>7.5, 15.9, 15.0</td>
<td>8.0, 15.7, 15.0</td>
</tr>
<tr>
<td>$\beta_{N}^\text{th}, \beta_{N}^\text{fast}$</td>
<td>2.3, 0.1</td>
<td>2.2, 0.23</td>
<td>2.3, 0.36</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>5.5</td>
<td>6.0</td>
<td>7.5</td>
</tr>
<tr>
<td>$H_{98}$</td>
<td>0.95</td>
<td>0.99</td>
<td>1.13</td>
</tr>
<tr>
<td>$f_{\text{BS}}$</td>
<td>0.53</td>
<td>0.52</td>
<td>0.66</td>
</tr>
<tr>
<td>$n/n_{\text{Gr}}$</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>$P_{\text{fusion}}, P_{\text{aux}}, \text{ MW}$</td>
<td>185, 92.5</td>
<td>518, 129</td>
<td>754, 116</td>
</tr>
<tr>
<td>$Q, Q_{\text{engr}}$</td>
<td>2.0, 0.51</td>
<td>4.0, 0.86</td>
<td>7.0, 1.11</td>
</tr>
<tr>
<td>$&lt;N_{w_{\text{pl}}}&gt;_{\text{pl}, \text{Nw}}^\text{peak,FW}$</td>
<td>0.71, 1.0</td>
<td>1.19, 1.67</td>
<td>1.21, 1.7</td>
</tr>
<tr>
<td>$q_{\text{div, peak}}$</td>
<td>6.0</td>
<td>10.7</td>
<td>9.88</td>
</tr>
<tr>
<td>$\Delta I_B$ to $\text{TF coil, cm}$</td>
<td>87 (includes CS)</td>
<td>123</td>
<td>129</td>
</tr>
<tr>
<td>Cu $\text{TF/CS/PF}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\eta_{\text{th}} = 0.35$
Zoom-Out: Examine the R&D Flow Over Pre-FNSF, FNSF, and into DEMO

- Fusion neutrons material science
- Tritium science
- Integrated blanket testing
- Liquid metal breeder science
- Plasma-material science
- Enabling technologies (H/CD, fueling, pumping, diagnostics, magnets, BOP)
- Predictive simulation

DEMO